Journal of Evolving Space Activities
Vol. 2, Article No. 146, 2024
DOI: 10.57350/jesa.146
Research Note

Time-of-Flight Measurements of Ion Beam Compositions in Electrospray Thrusters

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(Received August 24th, 2023)

Time-of-flight (ToF) mass spectroscopy for electrospray thrusters was constructed to investigate the species and fraction of ions in the beam and the presence of fragmentation, where a cylindrical shield was placed just in front of the collector. The shield was expected to prevent the detection of secondary species, which were recently found to be one of the vacuum facility effects. However, the shield seemed to have almost no effects on the ToF signals because the signal did not decrease to zero, and some particles were always detected as they had been detected without the shield. To examine the cause of this signal detection, the collector current was measured under the condition that the gate electrode completely blocked the ion beam. The results implied that the electrospray ion source also emitted some neutrals. The measurement system was reconstructed to detect ions using a high-speed amplifier to avoid neutral particle detection. Then, the results showed that the electrospray thruster was operating in the pure ion mode.

Key Words: Electric Propulsion, Electrospray Thruster, Ionic Liquid, Time-of-Flight

Nomenclature

I	:	current, A
L	:	length, m
m	:	mass, kg
V	:	voltage, V
t	:	time, s
Subscripts		
em	:	emitter

1. Introduction

In recent years, the number of launches of nanosatellites less than 10 kg has rapidly increased.[1] Because they can be launched in a short time and at a low cost, many universities and private companies have been employing them for research and commercial use. The missions using these nanosatellites have become more diverse, and satellite constellations and formation flights are planned. To achieve these missions, precise control of the relative position and attitude of the satellites is required, and the need for thrusters is increasing. As satellites become smaller, the size and power of the propulsion systems are limited. For such thrusters, electrospray thrusters attract attention.[2]

The electrospray thruster is one of the electric thrusters and uses ionic liquids as the propellant. Ionic liquids can exist as a liquid phase in vacuum, because their vapor pressure is almost zero.[3] Therefore, a high-pressure gas system is not required, which is necessary for conventional thrusters that use gaseous propellants. The feeding system is composed of capillary action and electric fields.[4] This propellant feed system can eliminate mechanical valves and contribute to precise position control.

Figure 1 shows an electrospray thruster, consisting of many emitters and an extractor.[5] When several kV is applied between the emitter and the extractor, a strong electric field is generated at the emitter tip, and ions are emitted from the ionic liquid.[6,7] The emitted ions are accelerated by the potential difference between the emitter and extractor electrodes, and the thrust is generated by the reaction force. The thrust per emitter is very small (several tens of nN);[8] thus, precise thrust control is possible by adjusting the number of emitters and the voltage between the emitters and extractor.

In order to fine-tune the thrust, a precise measurement of the thrust is necessary. However, the emitted ions include monomers and multimers, such as dimers and trimers, in which some neutrals are bound to the monomer. In addition, multimers can fragment into monomers and neutrals in the ion beam.[9] The composirion of the ion beams and this fragmentation must be investigated to evaluate the performance of a thruster.

Time-of-flight (ToF) mass spectrometry has been employed to determine the composition of the charged particles in the beam.[10] ToF determines the mass-to-charge ratio of the ion beam by measuring the traveling time over a known distance L. In a previous study, the ratio of ion species was determined by the ToF method.[11] However, the results included cases where the ToF signal increases in the ratio of heavy ion species, so it is not an ideal signal that converges to zero.[12] In this case, the

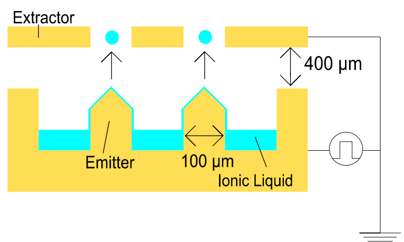

Fig. 1. Schematic of the electrospray thruster.[5]

zero point cannot be accurately determined, and the ratio of ionic species may be overestimated. Previous studies investigated the mechanism of secondary species generation in electrospray thrusters and its effect on thrusters in experiments in vacuum chambers.[13,14] These studies showed that secondary species were generated when the ion beam collided with the chamber surface, and the signal of the secondary species was included in the collector current. Thus, this signal should be removed because it does not occur without the chamber wall. The ToF experiment targets charged particles only and is not expected to detect neutral particles, but neutrals may be detected when a micro-channel plate (MCP) is used as a collector because some studies showed that MCPs were sensitive to neutral beams and strongly dependent on molecular weight and energy,[14–16] the MCP was expected to detect neutral particles, which could not be deflected by the gate electrode. In another previous study, a measurement system using a high-speed amplifier was constructed,[17] and this system can detect only charged particles. Although the detection of neutral particles is also important for ion beam characterization, a measurement system using a high-speed amplifier is constructed to understand the composition of the ion species alone.

In this study, the ToF measurements were conducted for an electrospray thruster, and the effects of secondary species and neutral particles from fragmentation were investigated. To reduce the effects of secondary species, a cylindrical shield was installed in the ToF system. Then, the MCP was examined to see if it collected neutral particles, and the results were compared when the MCP was changed to a high-speed amplifier.

2. Experimental Setup

The electrospray thrusters used in this study were fabricated using microfabrication techniques.[8,19] Figure 2 shows SEM images of the emitter utilized in the ToF measurements. Figure 3 shows typical examples of the time variation of the beam current at the emitter voltage of 2500 V. In the experiment, an 81-emitter chip was employed, where the emitters were approximately 100 μm in diameter. The distance between the emitters and extractors was 400 μm, and the extractor opening diameter was 300 μm.

Figure 4 (a) shows the setup when the MCP is used as a collector, and Fig. 4 (b) shows the setup when a high-speed amplifier (FEMTO, DHPCA-100) is used. The measurement system consists of a gate electrode to shut off the ion beam and a collector. After the beams are deflected, they arrive at the collector at different times due to the different velocities of the charged particles accelerated between the emitter and extractor electrodes. Because the lighter ionic species finish arriving first, the composition ratio of the ionic species is equivalent to the ratio of the current decrease to the total current detected at the collector. The time that the ions take to fly a certain distance between the gate and the collector is measured to obtain the mass-to-charge ratio.[20] A cylindrical shield of SUS304 with a diameter of 10 mm and a length of 0.441 m was installed upstream of the collector to prevent the intrusion of secondary species. ToF experiments were conducted with three distances L between the gate electrode and the collector: 0.441, 0.527, and 1.531 m. The difference in L is caused by differences in the way the measurement system is constructed, and L should be long enough to discriminate the mass of each ion species. In the first part of the ToF experiment using the MCP, the distance L between the gate electrode and the collector was set to L = 1.531 m. Then, L was set to 0.441 m to increase the signal-to-

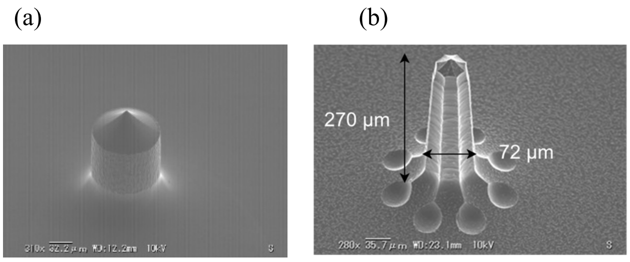

Fig. 2. SEM images of the emitter (a) without and (b) with grooves. Source of (b): Ref. 19), under CC BY 4.0 license. This figure is licensed under a Creative Commons Attribution 4.0 International License.

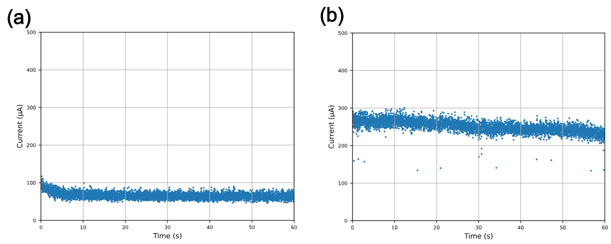

Fig. 3. Typical examples of the beam current from the thruster using emitters (a) without grooves and (b) with grooves.

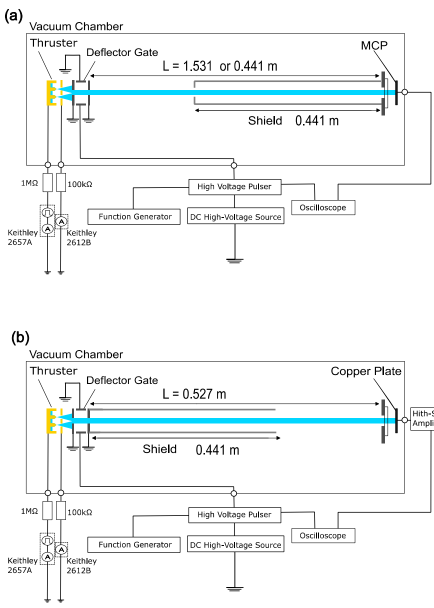

Fig. 4. Schematic of the time-of-flight measurements with a shield against secondary species using (a) the MCP and (b) the high-speed amplifier.

noise ratio. Using the high-speed amplifier, we also set L to 0.527 m in the ToF experiment. The difference in L between the last two (L = 0.441 and 0.527 m) is due to the different sizes of the MCP and the collector plate. The masses of the ions were calculated by measuring the time it took to travel from the gate electrode to the collector, where singly charged ions were assumed. The lightest mass arrives first at the collector. The signal detected by the collector was normalized. Three emitter voltages were set to 2500, 2700, and 2900 V, and the extractor electrode voltage was set to 0V (equivalent to the ground and chamber potentials). The measurement of negative ion beams using MCPs requires a special configuration, where the system was not readily available, similar to a previous study using a channeltron electron multiplier.[21] Therefore, the ToF experiments using MCP were conducted only for the positive emission mode in this study.

A square wave of 0 and 1000 V was applied to the gate electrode at 100 Hz while the ion beam was extracted. By applying the gate voltage, the ion beam was repeatedly deflected. An MCP was used as a collector. The amplified signal was averaged over 300 cycles using an oscilloscope (Tektronix, MSO46 4-BW-200), and the obtained signal was filtered using a Butterworth filter to improve the signal-to-noise ratio[19]. A ToF measurement system using a high-speed amplifier was also constructed, where a copper plate was used as a collector in place of the MCP in Fig. 4, and a high-speed amplifier (FEMTO, DHPCA-100) was connected to the outside of the chamber. The high-speed amplifier has a lower bandwidth than the MCP but can detect only charged particles. We used 1-ethyl-3-methylimidazolium dicyanamide (EMI-DCA) as the ionic liquid and dropped 0.01 μl onto the emitter surface. EMI-DCA is an ionic liquid that tends to emit ions in the purely ionic region and is a candidate as a propellant for electrospray thrusters.[22,23] We have employed EMI-DCA as the propellant after one of our previous studies.[24] In the experiments, the vacuum pressure was set below 4×10^{-4} Pa.

To verify the neutral beam detection, the extractor voltage was set to 0 V, and the emitter voltage was increased by 100 V in 1 s increments from 0 to 2500 V. A constant voltage of 1 kV was applied to the gate electrode so that the beam was constantly deflected while the neutral particles were not deflected. A SUS304 cylindrical shield with a length of 0.441 m and a diameter of 10 mm was installed at the upstream side of the collector. The distance L between the gate electrode and the collector was also set to L = 0.441 m.

3. Results and Discussion

Figure 5 shows ToF results for L = 1.531 m. Here, dashed red lines represent the masses of monomers, dimers, and trimers. The percentages were determined at the intersection of the red dashed line and the ToF signal. We obtained the ToF results for three applied voltages and showed the range of the three data. Decreases in signal at monomers, dimers, and trimers were detected, whereas a few ions larger than about 10^4 amu were also observed. The signal of monomers that are not fragmented decreases vertically at a mass of 111 amu, while the signal of monomers generated by fragmentation from dimers shows slopes between 111–288 amu. The proportion of monomers is 73–78%. The signal of dimers that are not fragmented decreases vertically at a mass of 288 amu, while the signal of dimers generated by fragmentation from trimers shows slopes between 288–465 amu. The proportion of dimers is 15–17%. The signal of trimers that are not fragmented should decrease vertically at a mass of 465 amu, but the decrease was almost undetectable. Thus, the proportion of trimers is sufficiently small compared with monomers and dimers. In this measurement, the signal-to-noise ratio was relatively low. To increase the signal-to-noise ratio, the distance L was shortened, and the emitter was replaced with the grooved emitter, resulting in approximately ten times the emitter current, as shown in Fig 3. To improve the signal-to-noise ratio, an emitter with shallow grooves was employed,[19] and L was shortened in the subsequent measurements.

Figure 6 shows ToF results for L = 0.441 m. The proportions of monomers, dimers, and trimers are 85–95%, 3–10%, and 0–2%, respectively. In the cases of the emitter voltages of 2700 and 2900 V, there are significant increases of 20–25% in the signal with a mass above 4×10^4 amu. Ideally, the signal converges to zero and does not increase. A previous study measured in a ToF measurement system without a shield showed a similar increase of approximately 5%.[12] These results show that the signal increase cannot be prevented even using the shield against the secondary species; thus, this signal implies that some particles other than secondary species from the chamber wall or secondary species are generated from the inside of the shield.

Figure 7 shows the MCP signals with the emitter voltages of 2900 and 0 V for L = 0.441 m. The signal with the emitter voltage of 2900 V has a minimum value of approximately −0.1 mV, whereas that of 0 V is constant at 0.1 mV, which is an offset. The minimum value of the ToF signal ideally equals the signal when 0 V is applied. This result shows that MCP detects and collects some particles constantly when applying the

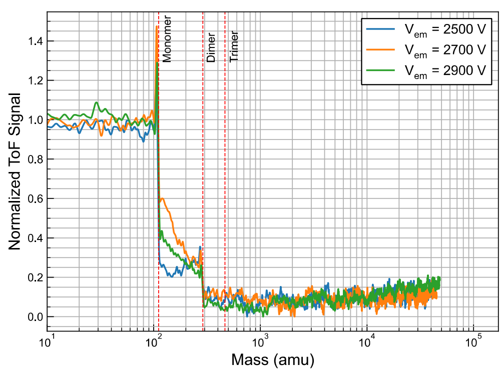

Fig. 5. Time-of-flight results for the three emitter voltages of 2500, 2700, and 2900 V for L = 1.531 m.

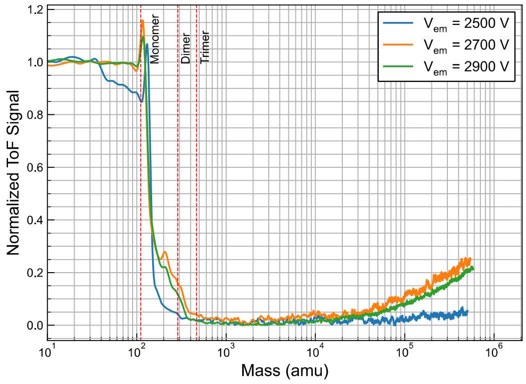

Fig. 6. Time-of-flight results for the three emitter voltages of 2500, 2700, and 2900 V for L = 0.441 m.

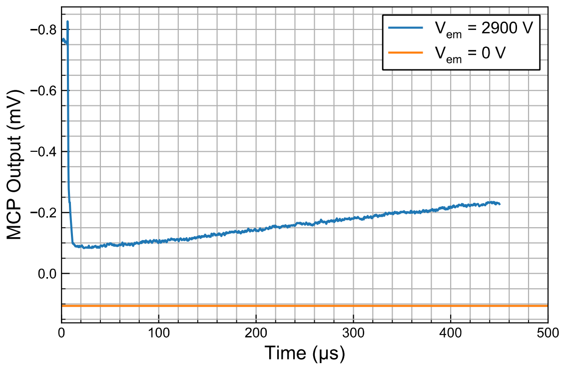

Fig. 7. Time-of-flight results for the emitter voltages of 2900 and 0 V for L = 0.441 m.

emitter voltage of 2900 V. MCP was expected to detect neutral particles, which could not be deflected by the gate electrode because of the sensitivity to neutral beams.[15–17)]

Figure 8 shows the result of the experiment to verify the neutral beam detection, where the emitter voltage, the emitter current, and the normalized MCP output are plotted. In the experiment, the gate electrode completely blocked the ion beam, and it was confirmed that the collector detected no ions. This result shows that the MCP signal increases as the emitter current increases, implying the amount of detection of neutral particles increases as the emitter current increases. Thus, the result indicated that the MCP detected neutral particles. Therefore, a more accurate ion beam evaluation can be performed by constructing a measurement system that does not detect neutrals.

Figure 9 shows the ToF result for L = 0.527 m using the high-speed amplifier. Decreases in signal at monomers, dimers, and trimers are observed. When applying the positive voltage, the signal of monomers that are not fragmented decreases almost vertically at a mass of 111 amu, while the signal of monomers generated by fragmentation from dimers shows slopes between 111–288 amu with a relatively large amount of noise. The signal of dimers that are not fragmented decreases at a mass of 288 amu, while it is hard to confirm the signal of dimers generated by fragmentation from trimers between 288–465

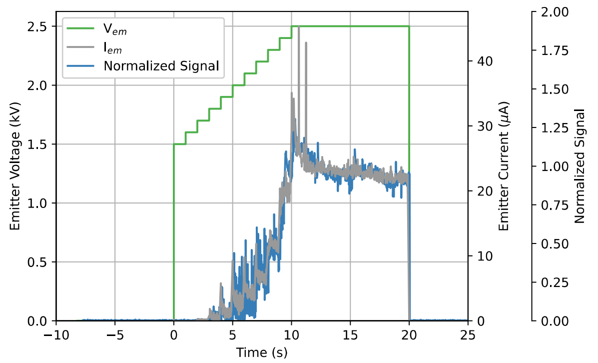

Fig. 8. Measurement results of the neutral particle verification.

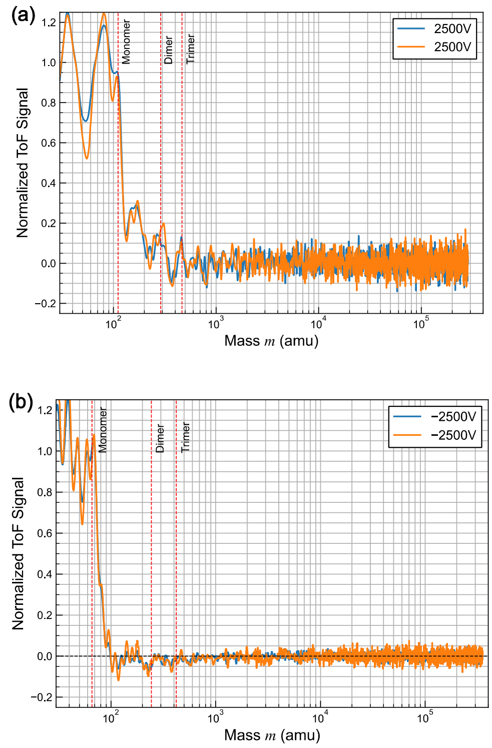

Fig. 9. Time-of-flight results for the two emitter voltages of 2500 and −2500 V for L = 0.527 m with high-speed amplifier.

amu. The proportion of monomers and dimers is determined to be more than 90%. The signal of trimers seems to be detected, but the portion cannot be obtained because of the low signal-to-noise ratio. However, the proportion of trimers should be sufficiently small compared with monomers and dimers.

When applying the negative voltage, the signal of monomers that are not fragmented decreases almost vertically at a mass of 66 amu, while the signal of monomers generated by fragmentation from dimers shows slopes between 66–243 amu. The proportion of monomers is more than 90%. The signal drops of unfragmented dimers cannot be observed at a mass of 243 amu. Thus, the negative ion beam seems to be mostly composed of monomers.

The ToF signal did not increase at masses higher than 4×10^4 amu, which was an issue in the measurements using the MCP, indicating that using a high-speed amplifier can prevent the detection of neutral particles that are not the target of the measurement. The results using the high-speed amplifier show that the thruster is operating in the pure ion mode, which is consistent with the results obtained using the MCP, except for the increase in the high mass-to-charge ratio. This increase is probably due to the neutral particles, but why the signal keeps increasing is still unclear. Secondary species might also affect the ToF signal. Further investigation is intended in the future.

4. Conclusions

A shield was installed in a ToF measurement system to suppress secondary species. The phenomenon of significant increases of 20–25% in the signal with a mass above 4×10^4 amu was shown, and the minimum value did not decrease to the line of the emitter voltage of 0 V. This indicates that some particles were constantly detected. When the gate electrode completely deflected the ion beam, it was shown that the MCP signal increased with the emitter current, implying a neutral emission from the electrospray thruster. To prevent detection of these neutrals, the measurement system using a high-speed amplifier was reconstructed, and the ion beam characteristics were evaluated. As a result, it was confirmed that the increase in the ToF signal at masses above 4×10^4 amu was not observed and that the thruster was operating in the pure ion mode, as in the measurements using the MCP.

Acknowledgments

This work was partially supported by JSPS KAKENHI, Grant No. JP21H01530, the Canon Foundation, the Advisory Committee for Space Engineering of Japan Aerospace Exploration Agency, and JST FOREST Program Grant No. JPMJFR2129.

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