Feasibility study of sublimable substance as an alternative propellant to xenon in ion thrusters

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Abstract: In recent years, deep space exploration has become popular throughout the world. Therefore, it is necessary to find a propellant that is cheaper and that can reduce the size and extend the life of the electric propulsion unit. Therefore, I examine the possibility of using a solid propellant with sublimation properties. First, the sublimation characteristics of the propellant were examined. It was found that the flow rate varied with temperature and recrystallization occurred at about room temperature. It was also confirmed that plasma ignition was actually possible.

I. Introduction

VARIOUS exploration plans are being made in many countries all over the world, and deep space exploration is expected to become more popular. And the performance of the electric propulsion becomes important. However, in the case of deep space exploration, there is a limit to electric propulsion that use xenon as a propellant. Xenon gas is present in the air only about $10^{-5}\%$ on the earth, and is very rare and very expensive. In addition, there is a limit to the amount of propellant that must be stored in a high-pressure tank and that can actually be transported. Furthermore, this makes it difficult to reduce the size of the electric propulsion. In other words, the use of xenon as a propellant may become an obstacle in the future in terms of the price, life, and size of electric propulsion unit.

The possibility of various propellants has been studied as an alternative propellant for xenon in electric propulsion unit. Examples include noble gases such as argon[1)] and krypton[2)], low melting point metals such as magnesium[3)] and bismuth[4)], and iodine[5)]. With regard to noble gases, there are disadvantages in that propulsion performance does not reach that of xenon, there are few merit in price, and storage density is low. Since bismuth and magnesium need to be heated, a certain amount of energy must be given, which is a disadvantage when power is

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limited. However, when high power can be used, propulsion performance exceeding xenon can be exhibited. Iodine is sublimable and has a storage density three times that of xenon, but it is toxic and difficult to handle. Although each has its own good points, it does not meet the purpose of this study. Therefore, based on the method using adamantane studied at Giessen University[6)], we considered the application of propellants of organic molecules with sublimation properties such as naphthalene and camphor. These substances are non-toxic or low because they are used in pharmaceuticals. In addition, it is very inexpensive compared to xenon, has a low vapor pressure and good storage properties. This can be expected to greatly reduce the high-pressure tank used to store xenon and entire system, and can also be miniaturized. Since it is solid at normal temperature and pressure, it is possible to transport more propellant when assuming an ion engine of the same size as that currently used. Therefore, it can be expected to extend the life in terms of the remaining amount of the propellant. In addition, the molecular weight is as large as 100 to 200, and the thrust does not drop significantly and may even exceed even when compared with xenon. The ionization energy is around 9eV, which is lower than 12eV of xenon, and the composition can be chosen freely. That is, it can be said that the sublimable propellant has a possibility of obtaining a propulsion performance superior to that of xenon at a price about 1/2 to 1/4 of that of xenon.

II. Objective

From the above, the objective of this study is to examine the possibility of sublimable substances as propellants in electric propulsion. Several substances have been adopted as propellant candidates. In this paper, we obtained the temperature and vapor pressure characteristics of three types of candidates and verified whether plasma ignition is possible.

III. Preliminary experiment

A. Experimental setup

The experiment was performed using the apparatus shown in Fig. 1. Each propellant was put in a test tube attached to a circled portion in Fig. 1, and the propellant was sublimated by heating the test tube with a heater. The temperature was measured using a thermocouple attached to the outside of the test tube, and the change in pressure was measured using a pressure gauge.

Fig. 1: Experimental setup

B. Experimental method

In this paper, we describe the results of naphthalene, adamantane and L-menthol. A summary of the materials used is summarized in Table 1. First, in a preliminary experiment, in order to confirm the sublimation characteristics of the substances used, the relationship between changes in temperature and pressure during sublimation was examined.

Propellant	Atomic weight/ molecular weight	Price [yen/100g]	Sublimation point[K]	Vapor pressure[Pa]
Xe Xenon	131.29	34,122	–	10(638K)
$C_{10}H_8$ Naphthalene	128.18	540	25	11(298K)
$C_{10}H_{16}$ Adamantane	136.18	13,810	–	–
$C_{10}H_{20}O$ Menthol	156.27	3,960	42～44	8.5(298K)

Table 1: Summary of propellants used

C. Result

The experimental results were as shown in Fig.2 to Fig.4 below. In the figure, the horizontal axis represents temperature (K) and the vertical axis represents pressure (Pa). Although there is a difference in the temperature at which sublimation begins for each substance, it was found that sublimation is performed at about 313 K without delay.

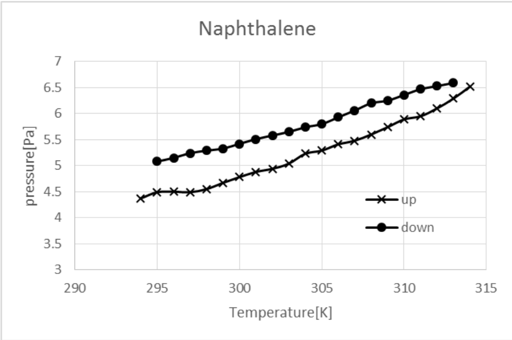

Fig. 2: Temperature vapor pressure measurement of naphthalene.

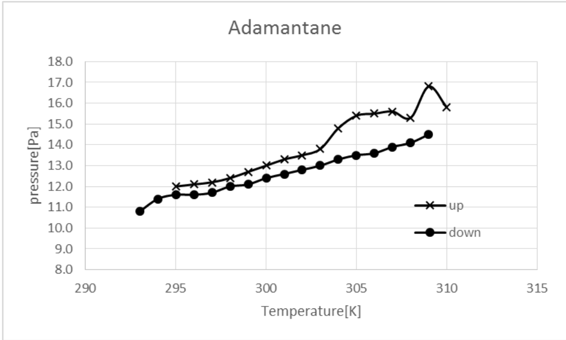

Fig. 3: Temperature vapor pressure measurement of adamantine.

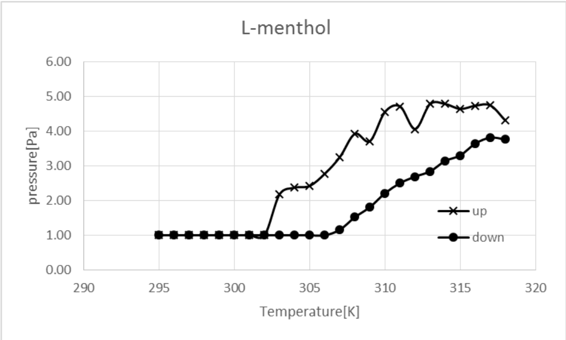

Fig. 4: Temperature vapor pressure measurement of L-menthol.

D. Discussion

From the results, it was found that sublimation can be controlled by temperature. It was also revealed that the sublimated substance recrystallized even at room temperature by actually sublimating. For this reason, it is necessary to heat not only the propellant but the entire propulsion unit. However, if the heating is about 313 K, there is a possibility that the heat generated when operating the ion thruster may be used. Moreover, since sublimation has not been performed uniformly, it is necessary to stabilize it by controlling temperature well.

IV. Main experiment

A. Experimental setup

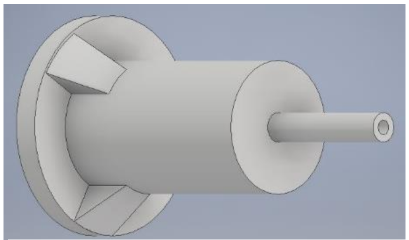

Fig. 5: Tank

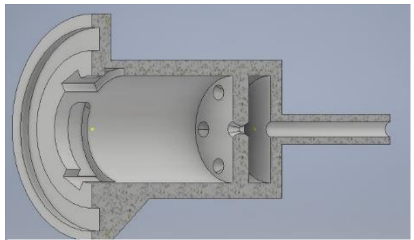

Fig. 6: Tank (Half)

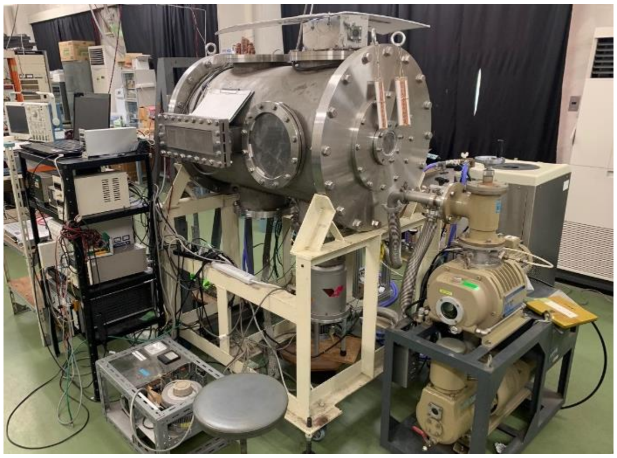

Fig. 7: Experimental setup

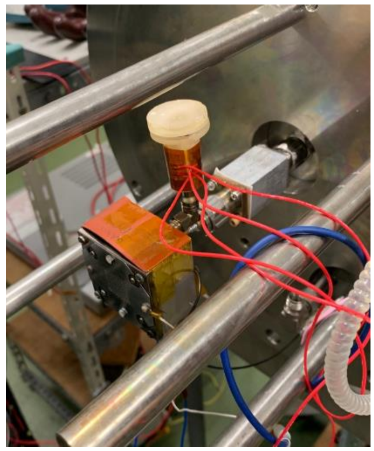

Fig. 8: Attaching the tank to the ion source

An advantage of a solid propellant with sublimation is that the shape of the propellant can be freely changed. So it can be transported to space in various forms according to the vacant space inside the propulsion unit. Thereby, it is possible to extend the life of the propulsion unit in the sense of eliminating the waste and the remaining amount of the propellant. Although the final goal is to use the propellant in various shapes in this way, in this experiment, a tank containing the propellant was created in order to achieve more efficient sublimation. The outline of the tank is shown in Fig 5, 6. The tank was created using a laboratory-owned 3D printer, and the experiment was conducted using the vacuum chamber shown in Fig 7. The tank was attached to the ion source as shown in Fig. 8 inside the cover of the vacuum chamber. In order to achieve steady sublimation, the outer periphery of the tank was surrounded by a heater, and the temperature was kept constant by changing the current.

B. Experimental method

This paper describes the results of confirming whether plasma ignition of L-menthol is possible. After the propellant was put in the tank and attached as shown in Fig. 8, the inside of the chamber was evacuated. At this time, the tank and the discharge chamber were not heated. When the vacuum was reached, the tank was heated, and if a change in pressure was observed, it was assumed that the propellant was sublimating, and microwaves were applied.

C. Result & Discussion

As a result, L-menthol could be plasma ignited. The state of ignition is shown in Fig 9. However, when starting the experiment, the chamber could not be completely evacuated. This is thought to be due to the propellant leaking out. In order to control this, it is considered necessary to attach a valve to the tank. Further, it is conceivable that the flow rate is excessively increased due to excessive increase in the temperature of the heater for heating the tank. As a result, the flow rate was more than 10 times the required flow rate. Further, as shown in Fig. 10, there was a liquid-like material in the tank where the propellant spouted out. It is necessary to consider whether it has become a liquid because the melting point of the propellant was exceeded due to an excessive increase in the temperature of the heater, or for other reasons. On the other hand, since the propellant was recrystallized at the cap, it was found that the entire tank had to be warmed. Also, since I didn't know how much the plasma was ignited, I ran too much microwaves. Thereby, as shown in Fig. 11, it was confirmed that the propellant was burnt and remained inside the discharge chamber.

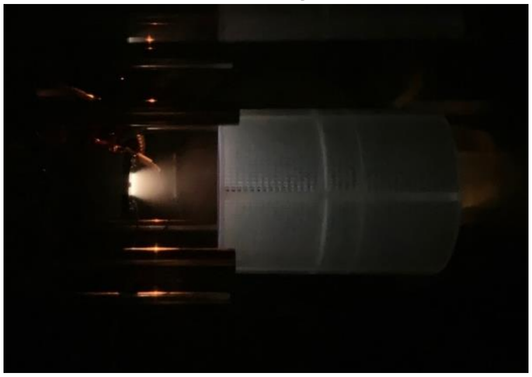

Fig. 9: Plasma ignition using L-menthol

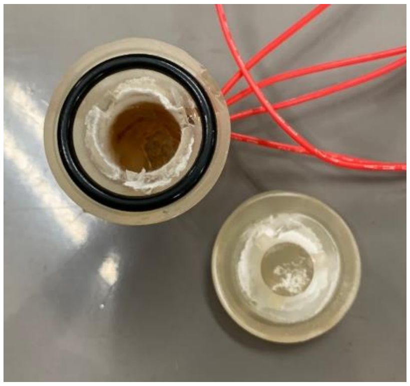

Fig. 10: Tank after experiment

Fig. 11: Inside the discharge chamber after the experiment

V. Conclusion

From the results of the two experiments, the following became clear.

・ Sublimation is possible by heating at about 313K.

・Recrystallization at about room temperature.

・Plasma ignition was possible for L-menthol.

・ Control by temperature alone is difficult and a valve is required.

Based on this, we will continue to measure thrust and ion current.

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