Feasibility Study of a Hybrid Thruster using Wire-Shaped Magnesium and Water for Application to Small Spacecraft*

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High thrust propulsion systems that can be used in small spacecraft are urgently needed to expand the use of small spacecraft. This study proposes a hybrid thruster for small spacecraft using wire-shaped magnesium as a fuel and water as an oxidizer. “Hybrid thruster” means that the in-space propulsion system generates thrust using a chemical reaction between a solid fuel and a vapor oxidizer, such as those utilized for hybrid rockets. Both magnesium and water are very safe, highly available, and very storable. To assess the feasibility of a hybrid thruster, we carried out experiments utilizing magnesium-wire combustion in water vapor at a pressure lower than the atmosphere, and estimated the input power for ignition, ignitability, and the average magnesium mass consumption rate. Then, propulsion performances were calculated using the experimental results, which show there is an input power of 2–3 W, with higher ignitability and a lower average mass consumption rate for thinner magnesium wires. The calculated specific impulse achieved its maximum at 323 s, with a mass mixture ratio of 1.25. At that mass mixture ratio, the calculated thrust using magnesium wires having diameters of 0.5 mm and 0.8 mm was 49.8 mN and 68.5 mN, respectively. Additionally, the applicability of the hybrid thruster was shown through a case study considering an existing deep-space mission.

Key Words: Small Thruster, Hybrid Rocket, Green Propellant, Magnesium, Water

Nomenclature

B : blue signal
 C_f : thrust coefficient
 C^* : characteristic velocity
 G : green signal
 I : discharge current
 L : relative corrected average luminance
 Nu : Nusselt number
 O/F : mass mixture ratio
 P : heat loss
 $\bar{P}_{in}$: average input power
 Q_{all} : total input energy
 R : red signal
 R_0 : plasma resistance
 SS : shutter speed
 T : temperature
 V : discharge voltage
 V_0 : amplitude of discharge voltage
 Y : average luminance
 $\tilde{Y}$: corrected average luminance
 d : diameter of magnesium wire
 d_e : nozzle exit diameter
 d_t : nozzle throat diameter
 h : heat transfer coefficient
 k : thermal conductivity
 l : magnesium wire length

$\dot{m}$: mass flow rate
 n : number of pixels
 p : pressure
 t : time
 x : axial direction of magnesium wire
 ε : emissivity of magnesium
 η : energy efficiency
 ρ : density of magnesium
 σ : Stefan-Boltzmann constant
 ω : angular frequency

Subscripts

H_2O : water
 Mg : magnesium
 a : ambient
 c : combustor
 f : final
 h : thermal convection
 i : initial
 ig : ignition
 k : thermal conduction
loss: loss
 r : thermal radiation
 s : standard
stop: stop
 w : inner wall of combustor

1. Introduction

These days, small spacecraft play a significant role in space due to the short time and low cost required for their development.¹⁾ A number of small spacecraft have been work-

ing on low Earth orbit (LEO), aiming to provide commercial services and technology demonstrations. However, the lack of a propulsion system suitable for small spacecraft has limited their missions. Such a system would enable attitude control, station-keeping, de-orbiting, and orbit transfer, and increase the variety of missions that can be carried out by small spacecraft. Propulsion capability is expressed by two major indexes: thrust and specific impulse, which are related to maneuvering time and velocity increment (ΔV), respectively.²⁾ Their product is proportional to the kinetic energy of the exhausted gas, and is limited by the available energy source. Which one of them should be prioritized depends on the mission type.

Thrust is required for short-time maneuvers, such as orbit transfer to deep space, avoidance of space debris, and controlled reentry to the Earth. The propulsion energy must be supplied in a limited time, and chemical energy is clearly more suitable than electric energy generated by a solar array panel in the case of a short-time restriction. The use of chemical propulsion entails an increased hazard risk due to an unexpected reaction of the propellants. Especially, safety is a key factor for small spacecraft that use ride-share launch and deployment from the International Space Station (ISS). Accordingly, the trend of developing “green propellants” has been accelerated. A green propellant is an environment-friendly propellant, unlike hydrazine which is commonly used in large spacecraft. Hydroxylammonium nitrate (HAN), ammonium dinitrate (ADN), hydrogen peroxide, and water are among those that have been widely studied as candidates for green propellants.^{3–8)}

Adding to the thrusters using those propellants, the trend of hybrid motors has been spreading.^{9–17)} A hybrid motor has the advantages of safety, based on the chemical stability of both the fuel and the oxidizer, and their separate installation. Whitmore et al. developed a hybrid motor that used acrylonitrile butadiene styrene (ABS) as a fuel and a mixture of nitrous oxide and gaseous oxygen as an oxidizer.^{9,10)} The advantages of ABS were reported to be its high availability and workability.¹⁰⁾ Nitrous oxide is a self-pressurizing propellant, so the lack of the necessity for an additional pressurizing gas is a good point of this oxidizer.⁹⁾ Additionally, the specific impulse was reported to be better when compared to a hydrazine thruster.⁹⁾ Jens et al. proposed a thruster using polymethylmethacrylate (PMMA) as a fuel and gaseous oxygen as an oxidizer. The targeted size of the thruster was from a 12 U CubeSat up to small spacecraft with a mass of 180 kg.^{13–16,18)} The prototype was fabricated and tested both in atmosphere and in a vacuum, and worked successfully.^{13–16)} Kamps et al. conducted a conceptual and experimental study regarding the apogee-motor for 100-kg or lighter satellites adopting high-density polyethylene (HDPE) as a fuel and nitrous oxide as an oxidizer.¹⁷⁾ This system also took advantage of the self-pressurizing property of nitrous oxide.¹⁷⁾ A lab-scale motor was tested in the atmosphere, showing the thrust to be on the order of 10 N.¹⁷⁾ Although such studies have been extensively conducted, they potentially include the following demerit. The disadvantage is that

oxidizers are stored in the tank at much higher pressure than the atmosphere. This means that the tank should be heavy. Solid- or liquid-state substances are favored for small spacecraft because their mass and volume are strictly limited.

One potential solution for a safe and suitable chemical propulsion is combustion of water and magnesium. Water has attractive features, such as its high safety, high availability, and high storability. Magnesium also has the same features. In particular, it is chemically stable and does not react with water under standard conditions. Nevertheless, at high temperatures, it has a high reactivity with water when compared to other metals such as aluminum or boron.¹⁹⁾ Huang et al. concluded from experimental results that the ignition temperature of magnesium in water vapor is 1178 K.²⁰⁾ Yuasa reported that the ignition temperature decreased in a moistened atmosphere compared to that in air or carbon dioxide.²¹⁾ There are several studies using water and magnesium for the propulsion system of launch vehicles or spacecraft, underwater propulsion, and hydrogen generation, and there are fundamental studies on the combustion characteristics.^{19,20,22–33)} Due to the higher reactivity, most of them basically used micro- or nano-size magnesium powder, which is not suitable for small spacecraft for three reasons. First, powder needs a carrier gas to be transported into a combustor. A gas system needs a high-pressure vessel, which would lead to an increase in the structural mass and volume. Second, the behavior of powder is unpredictable, which might reduce the reproducibility of combustion. Lastly, and most importantly, powder loses the safety features of metal due to the possible harm to human health and the risk of a dust explosion.

Bulk magnesium with a representative length on the millimeter or centimeter scale is desirable for small spacecraft propulsion systems, and there are a few studies regarding its use.^{20,24,25,28,29,33)} Coffin et al. conducted experiments with magnesium ribbons with a length of 4.6 cm in a gas mixture of oxygen, argon, and water vapor.²⁹⁾ They found that the mixture of water vapor led to the shortening of the burning time.²⁹⁾ Sakurai et al. proposed an energy cycle, the medium of which was magnesium.²⁸⁾ They observed combustion between a flake of magnesium with a typical size of $5.0 \times 0.5 \times 0.3 \text{ mm}^3$ and liquid water.²⁸⁾ Huang et al. suggested an underwater propulsion system that used a composite grain of magnesium powder, ammonium perchlorate, and hydroxyl-terminated polybutadiene as a fuel and water as an oxidizer.^{24,25)} As a fundamental study, they investigated combustion of spherical-shaped magnesium with diameters of 1.5–5.0 mm in water vapor at pressures of 50–80 kPa, obtaining the ignition temperature and the burning time, as well as clarifying the process of combustion.²⁰⁾ Nishii et al. tested combustion of magnesium wire with a diameter of 0.5 mm in 30 kPa water vapor by joule heating, and observed combustion with an intense flash.³³⁾ However, neither of them estimated either the applicability of combustion to small spacecraft or the propulsion performance resulting from combustion.

The present paper proposes a micro-propulsion system

based on combustion of “wire-shaped” magnesium in water vapor. The diameter of the wires was selected to be 0.2–0.8 mm, and there is no risk of health hazard or explosion. Furthermore, neither the wire-shaped magnesium nor water vapor necessitates any mixing processes. In the proposed thruster, the wire is burned from one end. Therefore, reignition is much easier because the shape of the fuel does not change. It should be noted that this study utilized the electrical-discharge method to initiate combustion from one end of the wires. For hybrid motors, several new ignition systems have been proposed, such as laser, arc-heating, a torch, or the decomposition of an oxidizer using a catalyst other than the conventional one of gunpowder and nichrome wire.^{11,12,14–16} This is because a conventional ignition system is not suitable for reignition. Additionally, gunpowder has the problem of the existence of a hazard. The electrical-discharge method is safe and suitable for reignition. The advantages of this method are mainly the following two points. One is the simplicity of the setup for ignition: it is especially feasible because the fuel is a metal. The other is the exclusion of other chemical substances, which are inevitable when gunpowder, a catalyst, or other chemical substances are used for ignition. The purpose of this study is to assess the feasibility of a hybrid thruster using water and wire-shaped magnesium for small spacecraft. Here, “hybrid thruster” means an in-space propulsion system for spacecraft that generates thrust through a chemical reaction between a solid fuel and a vapor oxidizer, such as a hybrid rocket. First, combustion of a magnesium wire and water vapor was examined under various conditions, changing the wire diameter and water vapor pressure. Second, the propulsion performance was estimated based on the obtained experimental results, and its applicability to small spacecraft was assessed.

2. Method

2.1. Testing system

A schematic of the experimental setup is shown in Fig. 1. The gas system was composed of a water tank, feed lines, and a combustor, all of which were surrounded by the atmosphere. The water tank was filled with deionized water and had a heater in it. Liquid and vapor water were separated

by gravity and only water vapor was supplied to the combustor through the feed lines. Water vapor pressure in the combustor was controlled by the temperature of liquid water in the tank. The feed lines and the combustor were covered with tape heaters so as not to let water vapor condense. A leakage test was conducted before supplying water vapor in each trial. The valve between the combustor and water tank was closed and the combustor was left as it was. The leak rate of air was calculated by dividing the pressure difference before and after the test by the period of the test. Then, the leakage of the air was calculated by multiplying the leak rate and the period of each combustion trial. The partial pressure of air inside the combustor was estimated from the sum of the leakage of the air from the outside of the combustor and the pressure of the combustor before supplying water vapor in each trial.

The magnesium wires were obtained from Japan Fine Steel Co., Ltd. The wire diameters were 0.2 mm, 0.5 mm, and 0.8 mm. The purity of magnesium was above 99.5%. The edge was flattened using sandpaper before each trial using the magnesium wire with diameters of 0.5 mm or 0.8 mm, whereas it was not flattened before each trial using the wire with a diameter of 0.2 mm. The magnesium wire was heated through alternating-current discharge with a thoriated-tungsten (ThO₂-W) wire. The thoriated-tungsten wire had a diameter of 0.5 mm. Six centimeters of the magnesium wire and 4 cm of the thoriated-tungsten wire were set in the combustor at a gap of 2–5 mm and with an angle of 0–10 deg. The voltage from the outlet was increased from 100 V up to 10 kV using a variable transformer, Tokyo Rikosha Co., Ltd. model RSA-5, and an ignition transformer, LECIP Holdings Corp. model G10M23-ZC. The frequency of discharge was 50 Hz. In all of the trials, the voltage of the variable transformer was set to 80 V.

The appearances of combustion were recorded using a video camera, Panasonic DMC-GH4. The shutter speed was set in each trial, ranging from 0.0002 s to 0.01 s. The International Organization for Standardization (ISO) sensitivity and F-number were respectively 200 and 2.8 for all of the trials. The frame rate was 30 frames per second (fps). The pressure inside the combustor was measured using a Keyence AP-43 or a Nagano Keiki Co., Ltd. KP-15. The dis-

Fig. 1. A schematic of the experimental setup. The left side of the combustor shows the electrical circuit and the right side shows the flow path of water vapor. Inside the combustor, discharge occurred between the magnesium wire and the thoriated-tungsten wire to ignite the magnesium wire. The combustor was exhausted to reach vacuum conditions before supplying water vapor in each trial.

Table 1. Experimental parameters.

Test	#01	#02	#03	#04	#05	#06	#07	#08
Diameter of Mg wire, mm	0.2	0.2	0.2	0.5	0.5	0.5	0.8	0.8
Initial water vapor pressure, kPa	11.5	48.7	69.8	11.6	48.6	69.9	10.6	49.5
Water temperature, °C	46.0	77.0	93.8 [†]	48.5	79.7	93.8 [‡]	47.7	81.0
Trial number	4	7	6	5	5	3	6	6

[†]Temperatures of two among six trials were eliminated due to measurement mistakes.

[‡]Temperature of one among three trials was eliminated due to measurement mistake.

charge voltage and current were measured using a differential probe, model 700925 from Yokogawa Test & Measurement Corporation, and a clamp meter, model 411 from Pearson Electronics, Inc. Those data were stored in a logger, GRAPHTEC midi LOGGER GL900. The data sampling frequency was 1000 Hz.

The experimental parameters were the diameter of the magnesium wire d and the initial water vapor pressure $p_{\text{H}_2\text{O}}$. Table 1 shows the parameters for all of the tests. The water temperature is also shown in Table 1 because the initial water vapor pressure was controlled by the water temperature. Three data of water temperature were eliminated from Table 1 due to measurement mistakes. However, it had little effect on the results because the initial water vapor pressure was measured without mistakes.

2.2. Estimation of combustion

The moment of ignition and that of the end of combustion were detected from the videos taken. For each trial, the video was divided into images for every 1/30 s because the frame rate was 30 fps. Firstly, the luminance of each picture after t from the beginning of discharge was obtained using the following equation:

$$Y(t) = \frac{0.299R(t) + 0.587G(t) + 0.114B(t)}{n}, \quad (1)$$

where $Y(t)$, $R(t)$, $G(t)$, $B(t)$, and n are the average luminance, red signal, green signal, blue signal, and the number of pixels of each picture, respectively. Secondly, the difference in shutter speed (SS) between the trials was corrected:

$$\tilde{Y}(t) = \frac{SS_s}{SS} Y(t), \quad (2)$$

where $\tilde{Y}(t)$ is the corrected average luminance signal and subscript 's' is the standard value. Lastly, the dark state was subtracted as follows,

$$L(t) = \tilde{Y}(t) - \tilde{Y}(t_{\text{stop}}). \quad (3)$$

Here, $L(t)$ is the relative corrected average luminance and t_{stop} is the stop time of the recording. The moment when the relative corrected average luminance was more than 5% of the maximum value of each trial was recognized as the moment of ignition. The time from the start of discharge is denoted by t_{ig} . In the same way, the moment when it was below 10% of the maximum value was recognized as the moment of the end of combustion. The time from the beginning

of discharge is denoted by t_f .

The total input energy to the magnesium wire and the thoriated tungsten wire Q_{all} was calculated as follows,

$$Q_{\text{all}} = \int_0^{t_{\text{ig}}} VI dt, \quad (4)$$

where V and I are the discharge voltage and current, respectively, and $t = 0$ is the moment of the beginning of discharge.

Assuming that the voltage and current are sine waves, $V = V_0 \cos \omega t$ and $I = V_0/R_0 \cos \omega t$, the total input energy can be as

$$Q_{\text{all}} = \frac{1}{2} \frac{V_0^2}{R_0} \left(\frac{\sin 2\omega t_{\text{ig}}}{2\omega} + t_{\text{ig}} \right), \quad (5)$$

where V_0 , R_0 , and ω are the amplitude of the discharge voltage, plasma resistance generated between the wires, and the angular frequency, respectively. Part of the total input energy was lost to the surrounding gas. If the energy efficiency was η , the input power to both wires was ηQ_{all} . Allocation of the energy ηQ_{all} to each wire was decided by the direction of the discharge current. This is because the magnesium wire and the thoriated tungsten wire were equivalent as electrodes due to alternating-current discharge. Additionally, if the final incomplete cycle of the discharge voltage or current was neglected, then the average input power $\bar{P}_{\text{in}}$ was

$$\bar{P}_{\text{in}} = \frac{\frac{1}{2} \eta Q_{\text{all}}}{t_{\text{ig}}}. \quad (6)$$

In this study, the energy efficiency was 0.7.³⁴⁾ Using Eq. (5) and Eq. (6), the average input power was deformed as

$$\bar{P}_{\text{in}} = \frac{1}{4} \eta \frac{V_0^2}{R_0} \left(\frac{\sin 2\omega t_{\text{ig}}}{2\omega t_{\text{ig}}} + 1 \right). \quad (7)$$

In this case, ω was 100π rad/s and the first term on the right side is approximated as 0. Therefore, the average input power was

$$\bar{P}_{\text{in}} \approx \frac{1}{4} \eta \frac{V_0^2}{R_0}. \quad (8)$$

Equation (8) means that the average input power only depends on the plasma resistance R_0 because the amplitude of the voltage was the same for all of the experiments. Therefore, the average input power depends on the ambient pressure and the distance between the electrodes, as the plasma resistance depends on them.

The length of the magnesium wire was measured before and after each experiment. Denoting these by l_i and l_f , respectively, the average magnesium mass consumption rate $\dot{m}_{\text{Mg}}$ was

$$\dot{m}_{\text{Mg}} = \frac{\pi}{4} d^2 \rho \frac{l_i - l_f}{t_f - t_{\text{ig}}}, \quad (9)$$

where ρ is the density of magnesium. It is assumed that the magnesium mass consumption rate was constant during combustion.

Fig. 2. Appearances of combustion for the first trial of #08, whose parameters were a magnesium-wire diameter of 0.8 mm and an initial water vapor pressure of 47.5 kPa. The discharge time was 5.0 s. (a) Before ignition. (b) During discharge but before ignition. A green glow is visible. (c) The moment of ignition. Intense flashing is observed. (d), (e) During self-sustained combustion. (f) The moment at the end of combustion. (g) After combustion has finished completely. (h) After combustion. A white powdered residue sticks to the fixed end of the wire.

Fig. 3. Time profile of the combustor pressure and relative corrected average luminance for the first trial of #08. Time origin is the beginning of discharge. After 4.5 s, both parameters start to increase rapidly and reach maxima after approximately 5.9 s. The luminance also reaches a local maximum at 7.0 s as the product sticking to the magnesium wire falls off.

3. Results

The appearances of combustion for the first trial of #08 are shown in Fig. 2 as an example, for which the magnesium-wire diameter was 0.8 mm and the initial water vapor pressure was 47.5 kPa. Before ignition, the magnesium wire and thoriated tungsten wire were set in the combustor, as shown in (a). In (b), a glowing wire is visible, but this was before ignition. Additionally, a green glow is sometimes observed between the wires. (c) is the moment of ignition. Only the heated end of the magnesium wire is flashing intensely. During combustion, (d) and (e), the flashing area becomes larger and moves upward. White smoke can be seen around the magnesium wire. (f) is the moment at the end of combustion. The flashing area gets smaller and moves further up. (g) is after combustion finished completely. After combustion, a white powder adhered to the inner wall of the combustor and the combustor window. As shown in (h), a white powdered residue sticks to the fixed end of the wire. The time profile of the same experiment, the first trial of #08, is shown in Fig. 3. The origin of the time axis is the moment when discharge started. After 4.5 s, both the combustor pressure and

Fig. 4. Summary of the results of all of the trials regarding ignition and self-sustained combustion.

luminance increase rapidly. The ignition time of this experiment was 4.6 s. They reach the maxima after 5.9 s. The luminance attains its local maximum at 7.0 s. This is because of the product sticking to the magnesium wire falling off.

A summary of the experimental results regarding ignition and self-sustained combustion is shown in Fig. 4. Ignition was observed under all of the test conditions. For #02 and #06, ignition was observed in all of the trials. The probability of ignition is lower for the 0.8-mm wire than for the thinner wires. The trials that were not recognized as self-sustained combustion are described as “only ignition” in Fig. 4. In #07, no trials were judged as self-sustained combustion. The probability of self-sustained combustion is also lower for 0.8-mm wires. Figure 5 shows the mean value of the average input power $\bar{P}_{in}$ calculated based on Eq. (6). The trial numbers that were recognized as ignition are shown next to the plots. Seven data with mistaken measurements were eliminated from this graph. The pressure error comes from the accuracy of the pressure sensors. The power error comes from the uncertainties of the differential probe, clamp meter, and ignition time. The mean value of the average input power shows no significant difference for different wire diameters when the initial water vapor pressure is approximately 10 kPa or 50 kPa. It is around 2 W for the 10-kPa trials and 3 W for the 50-kPa trials. Compared to that, when the initial

Fig. 5. Dependence of average input power for ignition on initial water vapor pressure. The trial numbers where ignition was observed are shown next to the plots. Seven data with mistaken measurements were eliminated from this graph. The pressure error comes from the accuracy of the pressure sensors. The power error comes from the uncertainties of the differential probe, clamp meter, and ignition time.

water vapor pressure is approximately 70 kPa, the mean value of the average input power is eight times bigger for the 0.5-mm wire than for 0.2-mm wire, the value of which is approximately 1 W. In #06, the conditions of which were such that the wire diameter was 0.5 mm and the initial water vapor pressure was 69.9 kPa, one of the trials represented an average input power of 20.7 W, whereas it was 2.63 W and 2.15 W for the other trials. The reason for this is unclear, but the plasma resistance was somewhat smaller in one particular trial.

The reciprocal of the ignition time is considered as an indicator of ignitability because it gets bigger as the ignition time gets shorter. Owing to this method, the non-ignition data can be included estimating that ignitability is 0. Figure 6 shows the dependence of ignitability on initial water vapor pressure. The trial numbers for each condition are shown next to the plot. The pressure error comes from the accuracy of the pressure sensors. The error in ignitability comes from the uncertainty of the ignition time. Ignitability tends to be large when the magnesium-wire diameter is thin under the same pressure. The other tendency is that, as the initial water vapor pressure is high, ignitability increases in the cases of magnesium wire diameters of 0.5 mm and 0.8 mm, whereas in the case of the diameter being 0.2 mm, ignitability decreases. Aeration of the combustor was neglected: its effect on ignition is to be clarified in future research. The maximum partial pressure of the remaining oxygen was 7.1% of the initial water vapor pressure.

Figure 7 shows the dependence of the average magnesium mass consumption rate on the initial water vapor pressure. The trial numbers that were recognized as self-sustained combustion are shown next to the plots. The pressure error comes from the accuracy of the pressure sensors. The error in the average magnesium mass consumption rate comes from the camera frame rate of 1/30 s and accuracy in measuring the wire length. None of the trials were determined to be self-sustained combustion in #07, as shown in Fig. 4; the

Fig. 6. Dependence of reciprocal of ignition time on initial water vapor pressure. The trial number for each condition is shown next to the plots. The pressure error comes from the accuracy of the pressure sensors. The error in ignitability comes from the uncertainty of the ignition time.

Fig. 7. Dependence of average magnesium mass consumption rate on initial water vapor pressure. The trial numbers recognized as self-sustained combustion are shown next to the plots. The pressure error comes from the accuracy of the pressure sensors. The error in average magnesium mass consumption rate comes from the camera frame rate of 1/30 s and accuracy when measuring the wire length.

conditions of which were such that the wire diameter was 0.8 mm and that the initial water vapor pressure was 10.6 kPa. The average magnesium mass consumption rate is large when the wire diameter is thick under the same targeted initial water vapor pressure. However, there is no clear dependence on the initial water vapor pressure for the same wire diameter.

4. Discussion

4.1. Magnesium-wire combustion

The experiments demonstrated combustion of magnesium wire from one end in water vapor. The overall chemical equation is

The average input power $\bar{P}_{\text{in}}$ was recognized as the power necessary to initiate combustion. It was approximately 2–3 W in almost all of the cases. The results show that the

order of input power is sufficient for use in small spacecraft.³⁵⁾ It can be assumed that the green glow observed before ignition is the emission of magnesium oxide (MgO).³⁶⁾ The appearances of combustion shown in Fig. 2 are almost the same as those in Huang et al.²⁰⁾ A white smoke or powder was observed during and after combustion. It is believed to be magnesium oxide, generated according to the overall chemical equation (Eq. (10)). The remaining magnesium oxide is assumed to be exhausted as applied to the actual thruster. Experiments in an open system should be the subject of future research.

The dependence of ignitability on wire diameter and initial water vapor pressure is discussed below. The dependence of ignitability on wire diameter is caused by the difference in input power per cross-sectional area. The average input power for initiating combustion is almost the same in all of the cases, as shown in Fig. 5. The ignition temperature is achieved faster because the input power per cross-sectional area of the wire is large for thin wires. Ignitability increases as the initial water vapor pressure increases in the cases of the wire having a diameter of 0.5 mm or 0.8 mm. It can be induced by reduction of the heat loss to the surrounding area. The overall heat loss P_{loss} is described as the sum of those through thermal conduction P_k , radiation P_r , and convection P_h , such as

$$P_{\text{loss}} = P_k + P_r + P_h. \quad (11)$$

Hereafter, the ignition temperature of the magnesium wire is assumed not to depend on the initial water vapor pressure. Furthermore, the temperature of the magnesium wire is assumed to be distributed only in the axial direction, expressed as x . The heat loss through thermal conduction is given as

$$P_k = \frac{\pi}{4} d^2 k_{\text{Mg}} \frac{T_{\text{Mg}}|_{x=l_i} - T_w}{l_i}, \quad (12)$$

where k_{Mg} is the thermal conductivity of magnesium, T_{Mg} is the temperature of the magnesium wire, and T_w is the temperature of the inner wall of the combustor. The heat loss through thermal radiation is given as

$$P_r = \int_0^{l_i} \pi d \varepsilon \sigma (T_{\text{Mg}}^4 - T_w^4) dx, \quad (13)$$

where ε is the emissivity of magnesium and σ is the Stefan-Boltzmann constant. When the initial water vapor pressure is high, the temperature of water vapor is also high. In addition, the inner wall of the combustor is set to a higher temperature, which means that the temperature of the inner wall of the combustor T_w is high when subjected to the higher initial water vapor pressure. Therefore, reducing the temperature difference between the magnesium wire and inner wall of the combustor results in reducing the heat loss due to thermal conduction and radiation. As for thermal convection, it is given as

$$P_h = \int_0^{l_i} \pi d h (T_{\text{Mg}} - T_a) dx, \quad (14)$$

where h is the heat transfer coefficient and T_a is the temper-

ature of water vapor. In more detail, the heat transfer coefficient is given as

$$h = Nu \frac{k_{\text{H}_2\text{O}}}{d}, \quad (15)$$

where Nu is the Nusselt number and $k_{\text{H}_2\text{O}}$ is the thermal conductivity of water. When the initial water vapor pressure increases, which is also accompanied by an increase in the water vapor temperature T_a , the temperature difference decreases. On the other hand, the heat transfer coefficient h increases at the same time. Therefore, the heat loss through thermal convection may increase or decrease. It should be noted that the effect of thermal convection is small in a vacuum; its change would not affect the overall heat loss. Totally, the overall heat loss will decrease when the initial water vapor pressure is high. The reduction in heat loss to the surrounding area contributes to shortening the ignition time as a result. The same trend was expected for wire with a 0.2-mm diameter, but a different trend appeared. Ignitability is the same or decreased as the initial water vapor pressure increased. The following two assumptions are the possible reasons. The first is that the heat loss to the surrounding area would be larger than when using a thicker wire due to the difference in the dependence of each heat loss in Eq. (11) when considering the magnesium-wire diameter. This difference may cause a change in the dominant heat loss term when the initial water vapor pressure increases. The second is that ignitability does not decrease as the initial water vapor pressure increases; it would actually be within the error margin. In order to reduce the error in ignitability, two improvements are suggested: use a high-speed camera to raise the frame rate, and use image analysis to measure the initial and final lengths of the magnesium wire.

The misfire affects the feasibility of the proposed thruster. Both ignited and not-ignited trials were experienced with most of the test conditions, as shown in Fig. 4. The misfire is caused by the difference in the heat input to the edge of the magnesium wire, which is equal to the reduction in energy efficiency η appearing in Eq. (6). The possible reasons for this are the conditions which were different between the trials that were categorized as the same test conditions. Based on these discussions, the possible reasons are listed below.

—Condition of magnesium wire edge. As mentioned in Section 2.1., the edges of the magnesium wires with diameters of 0.5 mm and 0.8 mm were flattened using sandpaper, whereas those of 0.2-mm diameter magnesium wire were not. However, the condition of the edges was only visually confirmed. The invisible differences in the edge conditions of the magnesium wires may lead to a difference in heat input.

—Distance or angle between the magnesium wire and thoriated tungsten wire. If the distance between the wires is longer, the heat loss to the surrounding gas increases. In addition, if the wires are misaligned, discharge heats not the edge of the magnesium wire but the side of it, leading to a decrease in the heat input per unit area.

—Partial pressure of air in water vapor. The composition of

Fig. 8. Comparisons of average magnesium mass consumption rate when the threshold is 1%, 5%, 10%, 15%, or 20% of the maximum relative corrected averaged luminance to determine the end of combustion. The difference was calculated based on the values applied 10-% threshold under each test condition. Negative values mean that the average magnesium mass consumption rates were smaller than that calculated using the 10-% threshold. In #07, no self-sustained combustion was observed, and no data are shown.

the gas might also contribute to a change in the heat transfer coefficient, which would then affect the amount of heat loss.

The thick wire shows a large average magnesium mass consumption rate. The reason for this tendency is presumed to be that the regression rates of the magnesium wires are approximately a constant value. This is due to the heat balance on the surface of the magnesium wire after ignition. The combustion heat and heat loss to the surrounding area balance per unit area of the magnesium wire. The thick wire has a large surface area, and therefore the average magnesium mass consumption rate is large.

In the image analysis, the end of combustion was recognized when the relative corrected averaged luminance fell below 10% of its maximum value, as mentioned in Section 2.2. Figure 8 shows the differences in the average magnesium mass consumption rate when the threshold is 1%, 5%, 10%, 15%, or 20% of the maximum value. The difference was calculated based on the values applied the 10-% threshold under each test condition. Negative values mean that the average magnesium mass consumption rates were smaller than that calculated using the 10-% threshold. In #07, no self-sustained combustion was observed, and no data are shown. The average magnesium mass consumption rate increases as the threshold increases under the same test conditions. This is because the burning time is calculated short. The maximum difference is 19% with test conditions of a magnesium wire with a diameter of 0.2 mm and the initial water vapor pressure of 11.5 kPa.

4.2. Feasibility study

4.2.1. Model of a hybrid thruster

This part assesses the feasibility of the hybrid thruster concept shown in Fig. 9 using the experimental results of #05 and #08, the targeted initial water vapor pressure of which was around 50 kPa and the diameters of the magnesium wires

Fig. 9. Conceptual diagram of the hybrid thruster, mainly composed of a combustor and a nozzle. Liquid water and magnesium wire are supplied to the combustor and are responsible for combustion. The hot combustion gas is accelerated in the nozzle and generates the thrust.

were 0.5 mm and 0.8 mm, respectively. It uses a magnesium wire as the fuel and water as the oxidizer. Hereafter, continuous steady combustion will be assumed. This thruster is composed of two chief parts: a combustor and a nozzle. A magnesium wire with a diameter of d and density of ρ is supplied to the combustor with the same velocity as the average magnesium mass consumption rate $\dot{m}_{Mg}$ under water vapor pressure of p_{H_2O} . A mechanical cable reel is one of the ways to compactly install the wire feeding system to the combustor, as shown in Fig. 9.^{37–39)} Liquid water is supplied with a mass flow rate of $\dot{m}_{H_2O}$, which is different from the experimental method where water vapor was supplied to the combustor. The supply of liquid water brings about two major differences. The first is that in the proposed thruster, liquid water vaporizes in the combustor, and the heat necessary for the temperature rise and vaporization of liquid water is compensated by the combustion heat. In the experiment, liquid water vaporized in the water tank, and the heater inside the tank was responsible for compensating the heat. The second is that there is a possibility that liquid water reacts with magnesium in the proposed thruster. To avoid quenching due to heat loss to liquid water on the surface of the magnesium wire, an appropriate liquid water injector should be installed in the proposed thruster. Water vapor and the magnesium wire react at the end of the wire. The combustion gas goes into a nozzle with a throat diameter of d_t , is accelerated, and then generates a thrust T . The total mass flow rate from the combustor $\dot{m}$ is

$$\dot{m} = \dot{m}_{Mg} + \dot{m}_{H_2O} = \left(1 + \frac{O}{F}\right) \dot{m}_{Mg}, \quad (16)$$

where O/F is a mass mixture ratio.

NASA Chemical Equilibrium with Applications (CEA) was used to calculate the characteristic velocity C^* , thrust coefficient C_f , and specific impulse I_{sp} for each assumed mass mixture ratio O/F .⁴⁰⁾ Two types of calculation were conducted: assuming equilibrium and frozen flow. The conditions for calculating the propulsion performance are shown in Table 2. In particular, the input total pressure p_c was set for each mass mixture ratio as the partial pressure of water vapor was equal to 49.5 kPa for a 0.5-mm magnesium wire and 47.8 kPa for a 0.8-mm wire, shown separately in Fig. 10.

Using the results of the CEA analysis, the thrust is calcu-

Table 2. Conditions for calculating propulsion performance.

Experimental results		
Diameter of Mg wire, mm	0.5	0.8
Initial water vapor pressure, kPa	49.5	47.9
Average magnesium mass consumption rate, mg/s	7.46	10.3
CEA input parameters		
Fuel	Mg	
Initial temperature of fuel, K	300	
Oxidizer	H ₂ O	
Initial temperature of oxidizer, K	300	
Nozzle expansion ratio	50	
Mass mixture ratio	0.50–4.00	
Total pressure	Shown in Fig. 10

Fig. 10. Total pressure as input parameters for CEA.

lated as

$$T = \dot{m}C^*C_f. \quad (17)$$

For estimating the size of the thruster, the throat diameter d_t is calculated using the equation

$$d_t = \sqrt{\frac{4\dot{m}C^*}{\pi p_c}}. \quad (18)$$

In addition, the combination of the throat diameter and nozzle expansion ratio of 50 enables estimation of the nozzle exit diameter d_e . Both the nozzle throat and exit diameters are set to satisfy the given conditions of the input total pressure, average magnesium mass consumption rate, and mass mixture ratio.

4.2.2. Feasibility study results

Figure 11 shows the calculational results of the vacuum specific impulse and thrust. The differences in the specific impulse with different wire diameters due to the differences in initial water vapor pressure were up to 0.07%, but the results for the 0.8-mm wire are not shown in the graph. In equilibrium flow, it reaches its maximum value at 323 s when the mass mixture ratio is 1.25, as plotted in the figure. The orders of magnitude agree with the results of Miller and Herr,²²⁾ who calculated the specific impulse of the system using magnesium powder and superheated water vapor at 500 K. The thrusts assuming an equilibrium flow are shown for both 0.5-mm and 0.8-mm diameter magnesium wires. The thrust

Fig. 11. Dependencies of specific impulse and thrust on mass mixture ratio. The specific impulse of a 0.5-mm diameter magnesium wire is shown. That of a 0.8-mm diameter wire is not shown because its difference from the 0.5-mm wire was less than 0.07%. The specific impulse assuming an equilibrium flow reaches its maximum value when the mass mixture ratio is 1.25, as plotted in this graph. The thrust assuming an equilibrium flow for both 0.5-mm and 0.8-mm diameter magnesium wires monotonically increases and ranges from 33 mN to 95 mN for the 0.5-mm wire and from 45 mN to 131 mN for the 0.8-mm wire. The thrust under a frozen flow was, at most, 9% lower than that under an equilibrium flow for both wire diameters, and they are not shown.

Table 3. Propulsion performance assuming a mass mixture ratio of 1.25 and an equilibrium flow.

Items	Values	
Diameter of Mg wire, mm	0.5	0.8
Specific impulse, s	323	323
Thrust, mN	49.8	68.5
Nozzle throat diameter, mm	0.63	0.75
Nozzle exit diameter, mm	4.45	5.30

under a frozen flow was, at most, 9% lower than that under an equilibrium flow for both wire diameters, so they are not shown. It monotonically increases and ranges from 33 mN to 95 mN for the 0.5-mm wire and from 45 mN to 131 mN for the 0.8-mm wire. Hereafter, the mass mixture ratio of 1.25 and an equilibrium flow will be assumed. The specific impulse, thrust, and diameters of the nozzle throat and exit are shown in Table 3. The thrust is 49.8 mN for the 0.5-mm wire and 68.5 mN for the 0.8-mm wire. The thrust and specific impulse of the proposed thruster is the same as those of the existing chemical propulsion systems for small spacecraft.³⁵⁾ The proposed hybrid thruster is superior over existing chemical propulsion system in terms of the safety of the fuel and oxidizer.³⁵⁾ The nozzle throat diameters are approximately 0.7 mm and the nozzle exit diameters are approximately 5 mm for wires with diameters of both 0.5 mm and 0.8 mm. The size of the nozzle is small enough to be installed in small spacecraft and practical for manufacturing. The nozzle jam due to the combustion products of magnesium oxide should be resolved at the time of actual application.

The mission shown in Funase et al.⁴¹⁾ was picked as a reference mission for a case study in addition to calculating the propulsion performance. The overview of the mission is that a 6U CubeSat traveled towards an Earth–Moon libration

orbit and conducted some scientific missions.⁴¹⁾ A resistojet thruster propelled by water was installed on the spacecraft and was in charge of generating the thrust.^{41,42)} This part assumes the substitution of the hybrid thruster proposed in this study for the resistojet thruster. Two types of comparisons were made. The first analysis was the firing time to acquire a delta-V of 6 m/s, which was required for the spacecraft's critical maneuver conducted one day after separation from the launch vehicle.⁴¹⁾ The second analysis was the total delta-V. The former is for estimating the thrust and the latter for the specific impulse. The mass, mass flow rate of the water, and specific impulse of the water resistojet thruster were quoted from Nishii et al.⁴²⁾ As for the hybrid thruster, a mass mixture ratio of 1.25 and equilibrium flow was assumed for both cases of wire diameters of 0.5 mm and 0.8 mm. The resistojet thruster was composed of three main parts: a tank, a vaporizer, and nozzles. Though the actual structures would be different for the two different thrusters, three crucial assumptions were made for installing the hybrid thruster in the CubeSat. The first was that the combustor and nozzle were replacements for the vaporizer and nozzles in the resistojet thruster, the total mass of which was maintained. The second was that the feeding system of the magnesium wire weighed 0.6 kg, which was calculated from CUA,³⁹⁾ which utilized a mechanical cable reel for the propellant supply. The structural mass of the CubeSat increased by 0.6 kg due to addition of the feeding system. The third was that the total mass of the propellant was the same as that of the resistojet thruster. This meant that the total propellant mass of 1.2 kg was divided into 0.533 kg of magnesium wire and 0.667 kg of water, assuming a mass mixture ratio of 1.25.

The results are shown in Table 4. The firing time for acquiring a delta-V of 6 m/s is shortened to approximately 8.0% for the 0.5-mm wire and 5.9% for the 0.8-mm wire. The mission time could be shortened using the hybrid thruster. The total delta-V of the hybrid thruster is 4.5 times larger than that of the resistojet thruster even though the same mass of propellant was assumed to be used. This clearly shows the superiority of the hybrid thruster in terms of the specific impulse. From all of the results listed above, it can be said that the hybrid thruster has a good potential to be used as a delta-V thruster for small spacecraft.

5. Conclusion

In this study, a hybrid thruster was proposed as a high-thrust propulsion system. It uses “wire-shaped” magnesium as the fuel and water as the oxidizer. Their combustion was examined and then the propulsion performance was estimated based on the experimental results. The conclusions are presented below.

—Magnesium wire ignition and combustion were recognized in water vapor at pressures lower than atmospheric pressure because the appearance of combustion consisted well with previous studies. The input power for ignition was typically 2–3 W, which is affordable for small spacecraft. Ignitability was higher for thinner diameters of the

Table 4. Application of hybrid thruster to actual mission.

Mission requirements and conditions			
Delta-V, m/s ⁴¹⁾	6	6	6
Thruster	Hybrid	Hybrid	Resistojet
Initial spacecraft mass, kg ^{39,41)}	14.6	14.6	14.0
Mass of mechanical cable reel, kg ³⁹⁾	0.6	0.6	—
Diameter of Mg wire, mm	0.5	0.8	—
Total mass of propellant, kg ⁴²⁾	1.20	1.20	1.20
Mass of Mg wire, kg	0.533	0.533	—
Mass of water, kg	0.667	0.667	1.20
Propellant mass flow rate, mg/s	16.8	23.1	6.08 ⁴²⁾
Specific impulse, s	323	323	68.5 ⁴²⁾
Results			
Firing time to acquire delta-V, hour	0.457	0.333	5.69
Total delta-V, m/s	271	271	60.2

wire. As for the dependence on the initial water vapor pressure, when the diameter of the magnesium wire was 0.2 mm, ignitability decreased as the initial water vapor pressure increased, and vice versa when the diameter of the magnesium wire was 0.5 mm or 0.8 mm. The average magnesium mass consumption rate was high for thick diameters of wire when the targeted initial water vapor pressure was the same, but it did not show a clear dependence on the initial water vapor pressure for the same wire diameter.

—Using the experimental results and the NASA CEA, the propulsion performance of the hybrid thruster was determined. The specific impulse was 323 s and achieved its maximum value when the mass mixture ratio was 1.25 under an equilibrium flow. In addition, the thrust was approximately 49.8 mN for a 0.5-mm wire and 68.5 mN for a 0.8-mm wire at that mass mixture ratio. The sizes of the thruster were estimated from the nozzle parameters, which were on the order of 1 mm, and the size is suitable for small spacecraft. The case study conducted based on the reference mission revealed that the hybrid thruster has sufficient propulsion performance to bring the required delta-V to small spacecraft in a short time using a restricted propellant mass.

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