Influence of Design Factors on the Thrust Performance of a Green Monopropellant Reaction System with Plasma*

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A green monopropellant reaction system that substitutes discharge plasma for conventional catalysts has been studied. This reaction system was developed for use in the 1 N thrusters of spacecraft reaction control systems. However, the thrust generated by this system was found to be only tens of millinewtons, with a thrust-to-power ratio of about 0.2 mN/W. To improve the thrust and thrust-to-power ratio of the reaction system, we studied and evaluated the effects of electrode axial gap, discharge chamber diameter, discharge type, electrode diameter, and target combustion chamber pressure on thrust and thrust-to-power ratio. All five factors except the electrode diameter had a main effect and four types of interaction on the thrust were confirmed. However, only the target combustion chamber pressure had a main effect on the thrust-to-power ratio and two types of interactions were confirmed. A thrust of 322 mN with a thrust-to-power ratio of 0.95 mN/W was achieved through system optimization.

Key Words: Hydroxylammonium Nitrate, Green Propellant, Ignition, Plasma, Design of Experiments

Nomenclature

- \( L_a \): electrode axial gap
- \( D_d \): discharge chamber diameter
- \( T_d \): discharge type
- \( D_e \): electrode diameter
- \( P_c \): target combustion chamber pressure
- \( t \): time
- \( F_{th} \): smoothed thrust
- \( f_{th} \): measured instantaneous thrust
- \( P_{th} \): thrust-to-power ratio
- \( I_{th} \): instantaneous current
- \( V_{th} \): instantaneous voltage

1. Introduction

Traditionally, hydrazine thrusters have been used in the reaction control system (RCS) of spacecraft. However, the handling cost of hydrazine is high because of safety aspects surrounding the protective equipment required to cope with the highly toxic hydrazine vapors. To reduce these risks and associated costs, several less toxic monopropellants, called green monopropellants, have been developed.1–5 These propellants have higher flame temperatures than hydrazine, making their theoretical specific impulses higher than that of the latter. However, conventional iridium-based catalysts cannot be applied to these green monopropellant systems because the high temperature and oxidizing atmosphere accelerate catalyst degradation.6,7) To employ green monopropellants in RCS thrusters, catalysts resistant to high temperatures and acidity, along with new reaction systems that avoid the use of catalysts, have been researched by several groups.8–10

Hydroxylammonium nitrate (HAN), based green monopropellants, have been developed in Japan.4,5) Our group has utilized a HAN-based propellant named SHP163,4) which is a mixture comprising HAN, ammonium nitrate, water and methanol at ratios of 73.6, 3.9, 6.2 and 16.3 weight percentage, respectively, and its adiabatic flame temperature is 2,400 K. Discharge plasmas have been applied to HAN-based green monopropellants in our laboratory as a substitute for conventional catalysts.11–13) It was necessary to ionize the gases to generate a plasma, and for this purpose, argon gas was fed into the reaction system along with the propellant12) so that the propellant reaction could be conducted in argon plasma. However, in a more recent study,13) it was found that the argon gas was unnecessary because gas could be generated from the liquid propellant by electrolysis and Joule heating. This system has a simpler structure than the system employing argon plasma and shows fast responses, with the propellant reaction initiated within a few milliseconds after the propellant came into contact with the electrodes. However, the thrust generated was only tens of millinewtons when the reaction system was attached to a thruster, which is much lower than the desired thrust of 1 N, and as such, the propellant reactivity must be improved.

Therefore, the objective of this study was to discover the factors affecting the thrust and thrust-to-power ratio by changing the reaction system geometry, discharge type, and target combustion chamber pressure. A thrust of 322 mN with a thrust-to-power ratio of 0.95 mN/W was achieved by optimizing the reaction system.

2. Experimental Methods

2.1. Factors evaluated

Five experimental factors were evaluated in this study: electrode axial gap, \( L_a \); discharge chamber diameter, \( D_d \); discharge type, \( T_d \); electrode diameter, \( D_e \); and target com-

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bustion chamber pressure, $P_c$. These factors were chosen for the following reasons. First, the discharge path length, controlled by the electrode axial gap, affects the discharge voltage$^{15, 16}$ and consequently the discharge power. Second, the discharge chamber diameter affects the pressure loss and discharge voltage, and thereby the thrust performance. Third, the discharge type DC and pulsed discharge can control the instantaneous discharge power, duty ratio and pressure in the region of the discharge path. Fourth, the plasma generated from the liquid propellant is affected by the electrode surface area.$^{15, 16}$ Finally, it has been reported that the linear burning rate of SHP163 depends on the ambient pressure, so the chamber lengths, 40 mm. On the other hand, the characteristic combustion chamber pressure and the theoretical specific impulse is 230 s. Each thruster has a combustion chamber length of 40 mm. On the other hand, the characteristic combustion chamber pressure was assumed to be constant at 230 s. Each thruster has a combustion chamber length of 40 mm. On the other hand, the characteristic combustion chamber pressure was assumed to be constant.

Schematics of the thrusters are shown in Fig. 1 and the levels tested for each of the factors evaluated are summarized in Table 1. Thruster throat diameters of 1.2 and 1.8 mm are employed in the design of experiments to carry out the experiments more efficiently. The $L_{16}(2^{15})$ orthogonal array shown in Table 2 was used to evaluate all of the interaction effects by testing all combinations would require at least 32 experiments. In this study, an orthogonal array was employed in the design of experiments to carry out the experiments more efficiently. The $L_{16}(2^{15})$ orthogonal array shown in Table 2 was used to evaluate all of the interaction patterns. The experimental conditions were defined by assigning each of the factors to the columns (1–15) and level respectively. Using this array, five main effects and 10 types of interactions could be evaluated from 16 experiments. The electrode axial gap, discharge chamber diameter, discharge type, electrode diameter and target combustion chamber pressure were assigned to columns 1, 2, 4, 8 and 15, respectively. Table 2 shows only 5 of the 15 columns, thus relations between all columns are shown in Fig. 2. Interactions between pairs of parameters can be evaluated using the other 10 columns. By way of example, the electrode axial gap $L_g$ was assigned to column 1 and the discharge chamber diameter $D_d$ was assigned to column 2. Their interaction ($L_g \times D_d$) is shown in column 3.

### 2.3. Experimental configuration

The experimental configuration is shown in Fig. 3. All experiments were conducted under vacuum conditions and the pressure inside the vacuum chamber was $<500$ Pa during the experiments. Discharge electrodes were connected to a DC-stabilized power supply (NISTAC: HV-2K10), and the maximum output current and voltage were fixed at 1 A and 1 kV, respectively. To limit the inrush current, a 470 Ω stabilizing resistor was inserted between the anode and power supply. When pulsed discharges were used, a 28 μF pulse discharge capacitor was connected between the electrodes and stabilizing resistor. A high-voltage probe (Tektronix P6015A) and a current probe (Tektronix TCP300 and TCP312) were used to record the discharge waveform. The thrust was measured by a thrust stand with a load cell (Kyowa LTS-200GA). The propellant was pressurized using nitrogen gas at 200 and 550 kPa, respectively.

### Table 1. Levels of the experimental factors.

| Factor                        | Levels                      |
|-------------------------------|-----------------------------|
| Electrode axial gap; $L_g$    | 0 & 4 mm                    |
| Discharge chamber diameter; $D_d$ | $\phi 2 & 4$ mm            |
| Discharge type; $T_d$         | DC & Pulsed                 |
| Electrode diameter; $D_e$     | $\phi 2 & 4$ mm            |
| Target chamber pressure; $P_c$| 550 & 250 kPa               |
| (corresponding throat diameter) | ($\phi 1.2 & 1.8$ mm)       |

### Table 2. $L_{16}(2^{15})$ orthogonal array used to define the experimental conditions.

| Column No. | Evaluation item | $L_g$ | $D_d$ | $T_d$ | $D_e$ | $P_c$ |
|------------|-----------------|-------|-------|-------|-------|-------|
| No. 1      | Experimental No. | 0 mm  | $\phi 2$ mm | DC    | $\phi 2$ mm | 550 kPa |
| No. 2      |                  | 0 mm  | $\phi 2$ mm | DC    | $\phi 4$ mm | 250 kPa |
| No. 3      |                  | 0 mm  | $\phi 2$ mm | Pulsed | $\phi 2$ mm | 250 kPa |
| No. 4      |                  | 0 mm  | $\phi 4$ mm | Pulsed | $\phi 2$ mm | 550 kPa |
| No. 5      |                  | 0 mm  | $\phi 4$ mm | DC    | $\phi 2$ mm | 250 kPa |
| No. 6      |                  | 0 mm  | $\phi 4$ mm | DC    | $\phi 4$ mm | 550 kPa |
| No. 7      |                  | 0 mm  | $\phi 4$ mm | Pulsed | $\phi 4$ mm | 550 kPa |
| No. 8      |                  | 0 mm  | $\phi 4$ mm | Pulsed | $\phi 4$ mm | 250 kPa |
| No. 9      |                  | 4 mm  | $\phi 2$ mm | DC    | $\phi 2$ mm | 250 kPa |
| No. 10     |                  | 4 mm  | $\phi 2$ mm | DC    | $\phi 4$ mm | 550 kPa |
| No. 11     |                  | 4 mm  | $\phi 2$ mm | Pulsed | $\phi 2$ mm | 550 kPa |
| No. 12     |                  | 4 mm  | $\phi 2$ mm | Pulsed | $\phi 4$ mm | 250 kPa |
| No. 13     |                  | 4 mm  | $\phi 4$ mm | DC    | $\phi 4$ mm | 550 kPa |
| No. 14     |                  | 4 mm  | $\phi 4$ mm | DC    | $\phi 4$ mm | 250 kPa |
| No. 15     |                  | 4 mm  | $\phi 4$ mm | Pulsed | $\phi 2$ mm | 250 kPa |
| No. 16     |                  | 4 mm  | $\phi 4$ mm | Pulsed | $\phi 4$ mm | 550 kPa |
500 kPaG to generate \( P_{hc} \) of 250 and 550 kPa, respectively.

In this study, polycarbonate was used as the body material for the reaction system because of its machinability. Polycarbonate is a flame-resistant resin, but it cannot resist the combustion flame temperature for a long period of time. As such, the operation time for all experiments was limited to 1.5 s to prevent heavy damage to the polycarbonate. The propellant valve and power supply were switched on and off simultaneously. The maximum thrust and thrust-to-power ratio during 1.5 s of operation were then evaluated.

### 2.4. Evaluation criteria

The thrust stand used in this study cannot measure instantaneous thrust because of its time response and the normal mode of the thrust stand appears as a thrust waveform. The thrust generated was therefore evaluated by smoothing the thrust waveform output from the load cell. The normal mode period of the thrust stand was 30 ms and the thrust was smoothed by taking the average of the measured waveform every 300 ms, 10 times the normal mode period. The following formula was used to smooth the thrust waveform

\[
F(t) = \int_{t-0.15}^{t+0.15} f(t) \, dt / 0.3
\]

where, \( F(t) \) is the smoothed thrust, \( t \) is time, and \( f(t) \) is the measured instantaneous thrust. The thrust-to-power ratio was also evaluated from smoothed thrust data. The thrust-to-power ratio was determined using

\[
P_{(t)} = \int_{t-0.15}^{t+0.15} \frac{f(t)}{I(t)V(t)} \, dt / 0.3
\]

where, \( P_{(t)} \) is the thrust-to-power ratio, and \( I(t) \) and \( V(t) \) are the measured instantaneous current and voltage, respectively.

### 3. Experimental Results and Discussion

#### 3.1. Maximum thrust and thrust-to-power ratio

Table 3 shows the maximum thrust and thrust-to-power ratios obtained in each experiment. In experiment No. 16, the thrust could not be measured because the thrust stand resonated at the frequency of the pulsed discharge that coincided with that of the normal mode. The thrust for experiment No. 16 was therefore estimated using successive approximations. Mass loss from the polycarbonate bodies were approximately a few milligrams in all experiments. The thrust generated from combusting a few milligrams of polycarbonate in 1.5 s of operational time was assumed to be a few millinewtons, which is much lower than the thrusts measured in this study (Table 3), and the effect of polycarbonate combustion on thrust could therefore be ignored. All columns in the orthogonal array (Table 2) were used in this study to evaluate 15 factorial effects, and thus the degree of freedom of the error was 0. Some errors were needed for analysis of variance and these errors were determined first. The sums of the squares of each column, representing the intensity of each factorial effect on thrust and thrust-to-power ratio, are shown in Figs. 4 and 5, respectively. Evaluation items to the left of the point at which the slope changes in each figure were assumed as the errors in this study. For the maximum thrust, \( L_e \times D_e - D_3 \times P_e \) in Fig. 4 were therefore regarded as being within the experimental errors. \( D_e \) electrode diameter) had a significant interaction with \( D_3 \) (discharge chamber diameter), thus the main effect of the electrode diameter was eliminated, as it was within the experimental error. For the thrust-to-power ratio, \( T_e \times D_e - D_3 \times T_3 \) in Fig. 4 were regarded as within the experimental error. \( D_3, T_3 \) (discharge type) and \( D_e \) were all found to have interactions that were eliminated as within the experimental error.

The analysis of variance table and the response graphs for thrust are shown in Table 4 and Figs. 6 and 7, respectively. The corresponding data for the thrust-to-power ratio are given in Table 5 and Fig. 8, respectively. In all cases, the significance level was defined by a \( P \)-value of \( \leq 0.1 \).
Extending the electrode axial gap increased the thrust, but the thrust-to-power ratio was not significantly affected and it was concluded that extending the gap increased the input discharge power, which in turn, increased the thrust. Using a discharge chamber inner diameter of 2 mm increased the charge power, which in turn, increased the thrust. Using a discharge chamber too much would reduce the thrust by causing high pressure losses and choking flow through the discharge chamber. Pulsed discharges increased the thrust, but did not affect the thrust-to-power ratio. This was attributed to changes in discharge power consumption upon changing the discharge type.

In contrast, higher target reaction chamber pressures increased both the thrust and thrust-to-power ratio. The combustion chamber pressure during operation probably rose higher under high target chamber pressure conditions because of the narrower throat diameter. It is believed that, under higher pressure conditions, the propellant linear burning rate became higher because the high chamber pressures led to increases in both thrust and thrust-to-power ratio. It is also assumed that the increase in thrust was related to the propellant mass flow rate.

The propellant feeding pressure was increased to generate the higher combustion chamber pressure. If the chamber pressure did not rise sufficiently during operation, the pressure between the propellant tank and injector would become much higher, leading to an increase in the propellant mass flow rate.

It was found that a synergistic interaction occurred between \( L_s \) and \( D_A \), with longer electrode axial gaps enhancing the effect of the discharge chamber diameter. In contrast, the...


$L_g \times T_d$ and $T_d \times P_{tc}$ interactions cancelled each other out, with the effect of discharge type being reduced by the longer electrode axial gap and the effect of chamber pressure being reduced by using pulsed discharges. Additionally, the $D_d \times D_e$ interaction affected the thrust when the electrode diameter was 4 mm because the $\phi 4$ mm electrode mounting holes expanded the diameter of the discharge chamber by 2 mm, as shown in Fig. 9.

### 3.2. Optimization experiment

To evaluate the reliability of the results, an experiment was conducted under the optimum conditions determined from the previous analysis. The experimental conditions were $L_g = 4$ mm, $D_d = 2$ mm, $T_d = \text{Pulsed}$, $D_e = 4$ mm and $P_{tc} = 550\text{kPa}$. The discharge and thrust waveforms from the experiment are shown in Fig. 10. Two types of thrust waveforms are shown in the figure: the raw thrust waveform $f(t)$, which was the direct output from the load cell; and the smoothed waveform $F(t)$, which was calculated using Eq. (1). The voltage fluctuation during the early phase of operation arises from charging and discharging of the pulsed discharge capacitor. After this phase, the discharge type was changed from pulsed to DC, with a discharge current of 0.4 A. Glow discharge occurred in the DC mode according to the current and voltage behavior. The maximum thrust obtained during this experiment was 322 mN with a thrust-to-power ratio of 0.95 mN/W. This thrust was a little lower than the 349 mN obtained in experiment No. 10, but
otherwise it was the second highest value compared with the thrust values in Table 3. Furthermore, the thrust-to-power ratio of 0.95 mN/W was the highest value obtained when compared with all of the values in Table 3. The results of the optimization study were therefore regarded as reliable.

4. Conclusions

In this study, we evaluated the effects of five factors on the thrust and thrust-to-power ratio. The factors (and levels) tested were the electrode axial gap (0 and 4 mm), discharge chamber diameter (2 and 4 mm), discharge type (DC and pulsed discharge), electrode diameter (2 and 4 mm) and target combustion chamber pressure (250 and 550 kPa). To discover the factors affecting the performance of this propellant reaction system, we evaluated the five factors experimentally using an orthogonal array. The thrust was increased using an electrode axial gap of 4 mm, a discharge chamber diameter of 2 mm, pulsed discharge, an electrode diameter of 4 mm and a target combustion chamber pressure of 550 kPa. The electrode axial gap, discharge chamber diameter, discharge type and target combustion chamber pressure had main effects and were also found to interact with one another. In contrast, the electrode diameter only interacted with the discharge chamber diameter. Significant effects on the thrust-to-power ratio were confirmed as being related to the target combustion chamber pressure. Under optimum conditions, a maximum thrust of 322 mN was generated with a thrust-to-power ratio of 0.95 mN/W.

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