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Performance of a green propellant thruster with discharge plasma

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ABSTRACT

A discharge plasma was applied to initiate the combustion of a hydroxylammonium nitrate-based propellant as a substitute for the catalysts that are typically employed. The resulting thrust and thrust-to-power ratio during short interval firing tests as well as the chamber pressure with a single pulse discharge were evaluated. A 1.5-s firing test generated a maximum thrust of 322 mN along with a thrust-to-power ratio of 0.95 mN/W. During the single-pulse discharge trials, pulsed discharge capacitor energies of 5.4, 10.8, and 16.4 J were assessed, and the maximum chamber pressure was found to increase as the energy was raised. The maximum chamber pressures varied widely between experimental trials, and a 16.4-J energy value resulted in the highest chamber pressure of over 1 MPaG. The time spans between the pulsed discharge and the peak chamber pressure were in the range of 1–2 ms, representing a chamber pressure increase rate much higher than those obtained with standard catalysts.

1. Introduction

Although hydrazine has been used in monopropellant thruster systems for many years, its toxicity and relatively high vapor pressure increase the associated handling costs because special protective equipment must be used. To reduce these costs, various low toxicity (so-called "green") propellants have been developed [1–4]. However, conventional monopropellant thruster catalysts cannot be applied to these green propellants because these propellants tend to generate higher flame temperatures and can also contain oxidizers, and the catalysts are unable to tolerate high-temperature and acidic environments [5]. To solve this problem, the development of catalysts resistant to high temperatures and acidity or the design of new reaction systems without catalysts is required.

In our laboratory, reaction systems based on plasmas for satellite attitude control thruster have been studied as substitutes for the use of conventional catalysts, working with hydroxylammonium nitrate (HAN) based propellant [6–8]. The HAN based propellant named SHP163 have been employed in our study, which is a mixture comprising HAN/ammonium nitrate/water/methanol in a ratio of 73.6/3.9/6.2/16.3 by weight percentage. In our latest work, a parametric study using an orthogonal array was conducted and showed that increasing the target chamber pressure increased both the thrust and the thrust-to-power ratio, while varying other parameters affected only thrust. The optimal conditions were found to be a 4-mm electrode gap, a ϕ 2-mm discharge chamber diameter, pulsed discharge, a ϕ 4-mm electrode, and a 0.55-MPa target chamber pressure. In the present work, the thrust and thrust-to-power ratio under these conditions were evaluated. In addition, new thrusters having a higher target chamber pressure was developed based on the results of this latest study, and its combustion chamber pressure when employing a single-pulse discharge was evaluated to understand the pressure behavior.

2. Materials and methods

2.1. Short-interval firing tests under vacuum condition

The reaction system used in this experiment is shown in Fig. 1. This system had a central ϕ 2-mm discharge chamber incorporating ϕ 4-mm electrodes attached with a 4-mm gap. A thruster with a ϕ 1.2-mm throat diameter was attached downstream of the reaction unit. Characteristics of the thruster are shown in Table 1. The experimental configuration is presented in Fig. 2. A pulsed plasma was generated using a 28-μF pulsed discharge capacitor inserted between a DC power supply and the electrodes. This capacitor was charged by a DC stabilizing power supply (NISTAC HV-2K10), applying a maximum output current and voltage of 1.0 A and 1.0 kV, respectively. A 470-Ω stabilizing resistor was inserted after the power supply to reduce the inrush current. The voltage and current were measured by a high-voltage probe (Tektronix P6015A) and a current probe (Tektronix TCP300 and TCP312), respectively. The thrust was determined using a thrust stand with a load cell (Kyowa LTS-200GA), calibrated by attaching various weights to generate the calibration data presented in Fig. 3. The accuracy of the thrust stand during static load measure-

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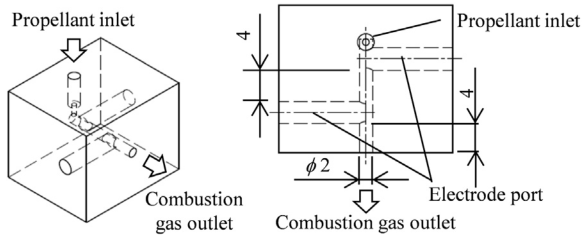

Fig. 1. Schematics of the reaction system. Left: Isometric view, Right: Bottom view.

Table 1
Characteristics of a thruster employed for short-interval firing test.

Target thrust	1 N
Target chamber pressure	0.55 MPa
throat diameter	1.2 mm
Characteristic length: L^*	0.7 m
Expansion ratio	11

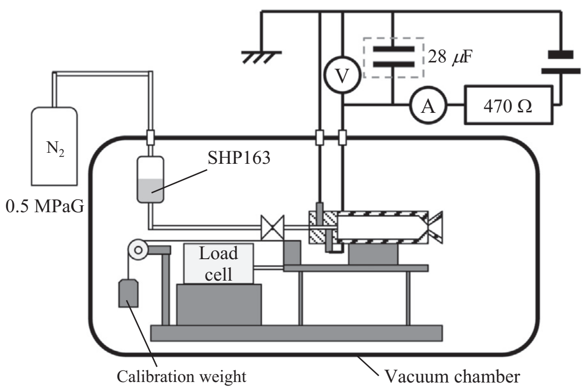

Fig. 2. Schematic of the experimental configuration employed for short-interval firing tests.

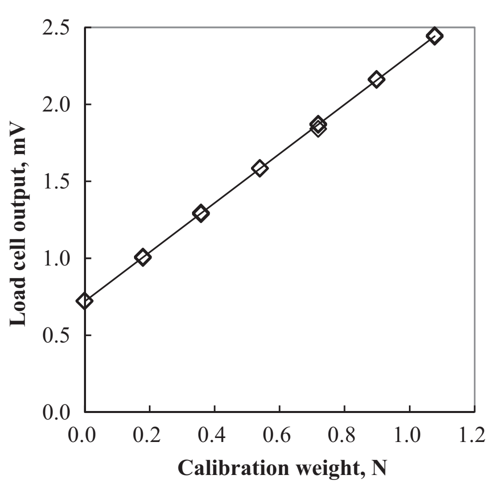

Fig. 3. Thrust stand calibration results.

ments was found to be better than ±1%. The propellant was pressurized to 0.5 MPaG with nitrogen gas and experimental trials were performed under vacuum conditions with the pressure maintained at less than 500 Pa throughout the experiment. At the each trial, the propellant valve and the DC power supply were switched on and off simultaneously. The propellant reaction body was made of polycarbonate to prevent damage to the reaction system by the plasma or combustion gases, and the system was operated for 1.5 s during each trial.

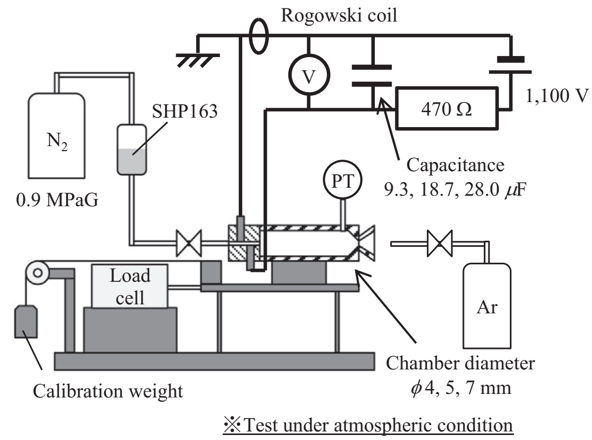

Fig. 4. Schematic of the experimental configuration for single-pulse discharge tests.

2.2. Single-pulse discharge tests under atmospheric condition

Combustion chamber pressure when employing a single-pulse discharge was evaluated by changing the discharge energy and combustion chamber volume. The pressure transducer meant for measurements of the chamber pressure could not be used under vacuum conditions, and therefore the experimental trials were conducted at atmospheric pressure. The experimental configuration is shown in Fig. 4. The discharge energy was varied by changing the capacitance between 9.3, 18.7, and 28.0 μF. The capacitors were charged to 1100 V, thus the corresponding electrostatic energies were 5.4, 10.8, and 16.4 J, respectively. Thrusters having a narrower throat diameter were employed in this study because the latest study showed that increasing the target combustion chamber pressure increase both the thrust and the thrust-to-power ratio. The combustion chamber length was fixed at 40 mm while the diameter was varied between ϕ 4, 5, and 7 mm. The thruster throat diameter was ϕ 0.85 mm, and thus the corresponding characteristic length, L^*, at each chamber diameter was 0.89, 1.38, and 2.71 m. The characteristics are summarized in Table 2. The reaction system employed during these trials was made of MACOR® and had the same geometry as that shown in Fig. 1. The propellant was pressurized to 0.9 MPaG with nitrogen gas and the trials were performed under atmospheric pressure. To prevent the combustion of methanol with air, the combustion chamber was first purged with a flow of argon from a position downstream of the thruster. The pulsed discharge current was measured with a Rogowski coil and the combustion chamber pressure was determined using a pressure transducer (KEYENCE AP-13S) with a maximum rating pressure of 1 MPaG and a 63% time constant of 1 ms. The operating procedure applied during these experiments was as follows.

1. Argon gas was forced through the thruster nozzle for more than 2 min so as to purge the combustion chamber.
2. The DC power supply was turned on to charge the capacitor, after which it was switched off.
3. The propellant valve was opened to inject propellant into the reaction system. The pulsed plasma was generated as soon as the propellant made contact with the electrode.
4. The argon purge was stopped after the pulse discharge was initiated.

Table 2
Characteristics of new thrusters employed for single-pulse discharge test.

Target thrust	1 N
Target chamber pressure	1 MPa
throat diameter	0.85 mm
Characteristic length: L^*	0.89, 1.38, 2.71 m
Expansion ratio	35