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# Design and development of direct-injection gas-hybrid rocket using glycidyl azide polymer for small satellite thruster

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## Abstract

This study proposes a GAP/$N_2O$ direct-injection type gas-hybrid rocket system, aiming at a small satellite thruster with high-density specific thrust without gunpowder. This is a simple system that eliminates the pressurization mechanism of the oxidizing agent by using nitrous oxide with a high vapor pressure using the self-exothermic decomposition characteristics of GAP, which is a high-density and high-energy fuel, and achieves high-density specific thrust. Here, the result of the experiment in which an average thrust of 350 N was generated using the blowdown system of $N_2O$ with the future satellite installation in the visual field is shown.

## 1. Introduction

Conventional hybrid rocket systems form boundary-layer combustion on the fuel surface. However, these propulsion systems have low fuel surface regression speeds because the evaporation rate of solid fuel is determined by the quantity of heat transfer from the boundary flame. The low regression rate induces an increase in the combustion surface owing to the large amount of fuel gas generated. Therefore, this system requires a long-length fuel or multi-port fuel grain; however, this results in low fuel density. Several studies were conducted to solve this problem; for example, an increase in fuel regression rate was confirmed with the swirling oxidizer flow technique owing to the increase in heat transfer, and tests were carried out up to a 5-kN thrust hybrid rocket motor [1]. As another approach, easy-to-melt materials are the focus as high-regression-rate solid fuels, such as paraffin wax, and low-melting-point thermoplastics. These materials have two-to-three times higher regression rates than conventional inert polymers [2,3]. By combining both types of research, further improvement of the fuel regression rate is expected. However, cylindrical shape fuel is used in current hybrid rocket systems and there is a lower-density fuel loaded in the chamber. Therefore, miniaturization development is difficult for small satellite thruster systems. This study proposes a new hybrid rocket system with high-density specific impulse. The new system employs a glycidyl azide polymer (GAP) highly energetic fuel and preserves the structure-mass ratio by excluding the pressure gas tank for oxidizer pressurization. This system is called a direct-injection type gas-hybrid rocket system. Stable combustion and high combustion efficiency has been reported for GAP fuel and gas oxygen in our previous study [4]. This study discusses the result of static firing tests using GAP fuel and nitrous oxidize ($N_2O$) as an oxidizer, and the $N_2O$ has a high steam pressure at room temperature, which is useful to blow down the feeding system.

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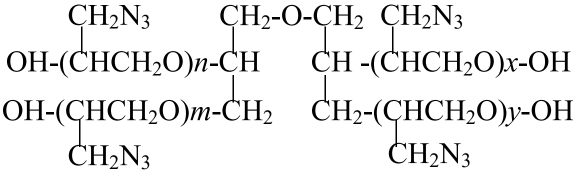
## 1.1GAP fuel

GAP is called a high energetic material because it has azide groups in its own chemical structure. Therefore, GAP is self-combustible and generates fuel-rich gas, which makes it possible to fuel gas-hybrid rockets. GAP also has a higher density than other polymers such as HTPB, and the high-density specific impulse enables the development of a small thruster system. Tetra-ol GAP, which is made by NOF Corporation, Japan, is used in this study. GAP contains four OH radicals as shown in Fig.1. GAP does not need an addition-agent like TMP, and it requires less curing reagent compared to conventional Di-ol GAP. Thus, increasing the pre-polymer content of GAP leads to a higher energy density and better mechanical properties. Moreover, GAP generates less combustion residue compared to conventional materials.



$$\begin{array}{ll} \mathrm{\ \ \ \ \ CH_2N_3\ \ \ \ \ \ \ \ \ CH_2\text{-}O\text{-}CH_2} & \mathrm{CH_2N_3} \\ \mathrm{OH\text{-}(CHCH_2O)}_{n}\mathrm{\text{-}CH} & \mathrm{CH\ \text{-}(CHCH_2O)}_{x}\mathrm{\text{-}OH} \\ \mathrm{OH\text{-}(CHCH_2O)}_{m}\mathrm{\text{-}CH_2} & \mathrm{CH_2\text{-}(CHCH_2O)}_{y}\mathrm{\text{-}OH} \\ \mathrm{\ \ \ \ \ CH_2N_3} & \mathrm{\ \ \ \ \ \ \ CH_2N_3} \end{array}$$

Figure 1: Chemical structural formula of tetra-ol glycidyl azide polymer

The theoretical performance of tetra-ol GAP and hydroxyl-terminated polybutadiene (HTPB) with $N_2O$ as the oxidizer is shown in Fig. 2 using the NASA CEA program [4]. The specific impulse (Isp) was calculated for tetra-ol GAP and HTPB under the following conditions; pressure of 2.5 MPa, nozzle expansion ratio optimization at sea level, assumed frozen nozzle. The specific impulse of GAP is slightly higher than that of HTPB. However, the densities of HTPB and GAP are $0.9 \times 10^3$ and $1.3 \times 10^3$ kg/m$^3$, respectively, and the density-specific impulse of GAP greatly exceeds that of HTPB. Moreover, the ratio of the low-density liquid oxidizer is smaller than that of HTPB owing to the low optimum O/F of GAP. GAP/$N_2O$ has a higher density-specific impulse than HTPB/$N_2O$. The low optimum O/F is because tetra-ol GAP has an oxygen atom in its molecular structure, which is advantageous in the design of small propulsion systems because, in general, liquid and gaseous oxidizers have low densities.

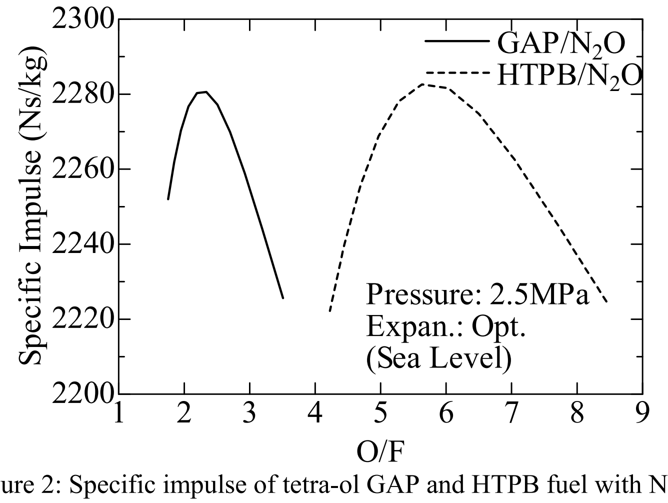


Figure 2: Specific impulse of tetra-ol GAP and HTPB fuel with $N_2O$

The linear burning rate for tetra-ol GAP was measured in our previous study [5]. Moreover, the combustion mechanism, which is the combustion efficiency, chemical degradation process, and so on, was reported by Hori et al. [6] and Wada et al. [7]. This study uses the following linear burning rate equation for GAP.

$$\dot{r}_b = 9.79P^{0.396} \qquad (1)$$

where ($\dot{r}_b$) is the linear burning rate [mm/s], $P$ the pressure [MPa], $n$ the burning-rate pressure exponent, and $a$ the proportionality constant.

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## 2. GAP/$N_2O$ direct-injection type gas-hybrid rocket motor testing

The direct-injection type gas-hybrid rocket system comprises two components: the oxidizer tank and combustion chamber. The benefits of this system include an increased propellant ratio and decreased structural coefficient compared to cylindrical shape fuel hybrid rockets. Additionally, the control of the fuel-residue ratio is easy because the fuel-mass ratio is determined by the combustion pressure and is independent of the oxidizer mass-flow rate. Therefore, the system is suitable for use in the thrusters of very small satellites with limited space. In this study, $N_2O$ is prepared an oxidizer that has a high vapor pressure. A schematic view of this system is shown in Fig. 3.

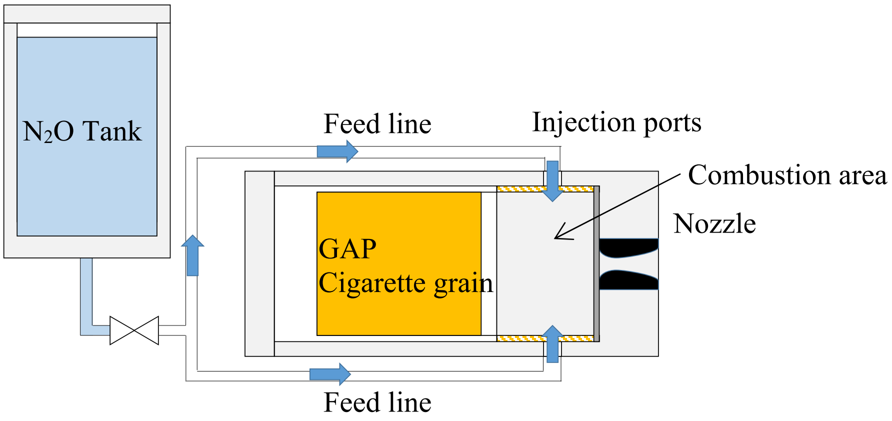

Figure 3: Schematic view of direct-injection type for hybrid rocket motor testing

### 2.1 GAP end-grain gas-generator test with 80-mm diameter motor

The GAP gas generator was first tested using an 80-mm diameter motor with an end-burning GAP grain as shown in Figs. 4 and 5.

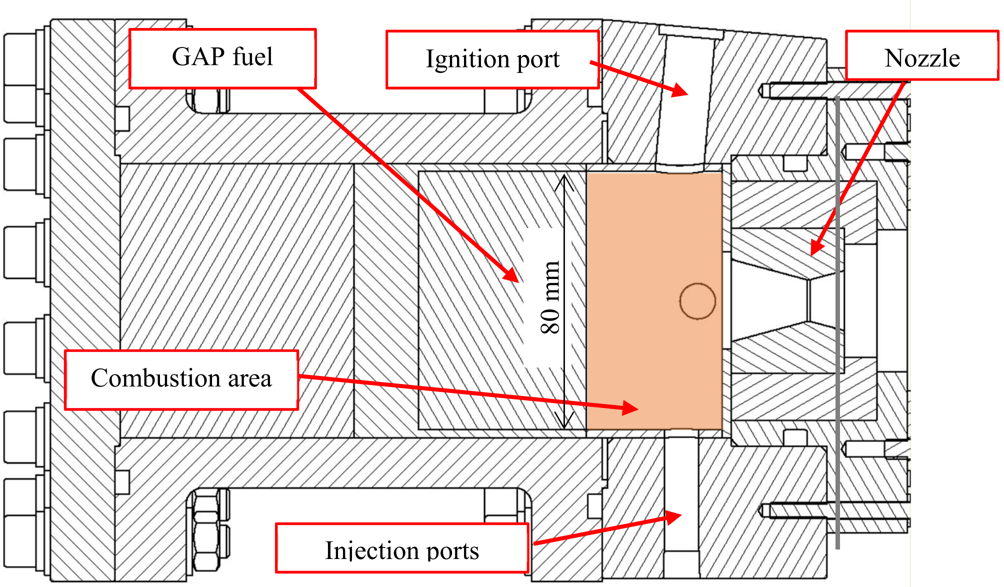

Figure 4: Schematic view of an 80-mm diameter motor case

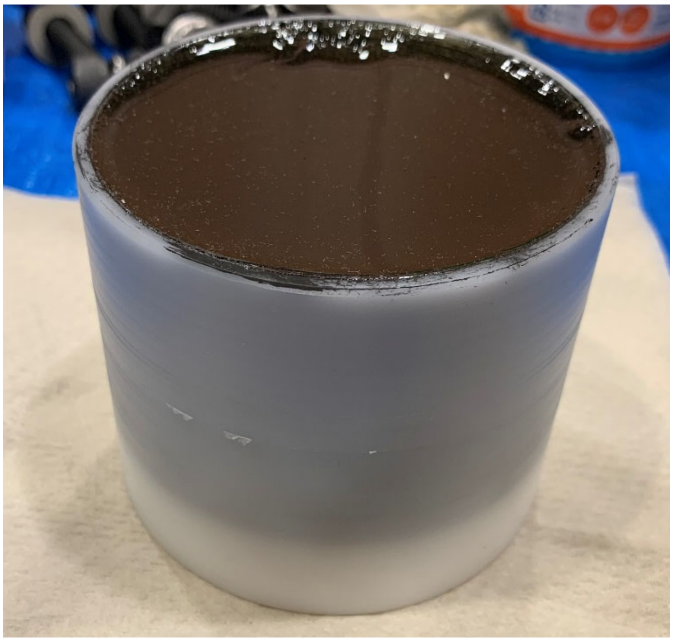

Figure 5: Cured tetra-ol GAP end-burning grain in the polyoxymethylene (POM) grain cartridge

The fuel was molded into a plastic cartridge. The diameter of the nozzle throat was determined using the following equation.

$$A_t = \eta_{c^*} \frac{\rho_{GAP} A_b \dot{r}_b {C^*}_{th}}{P_c}, \tag{2}$$

where $A_t$ is the nozzle area [m$^2$], $\eta_{c^*}$ the C* efficiency, $\rho_{GAP}$ the density of the GAP [kg/m$^3$], $A_b$ the burning area of the GAP surface [m$^2$], and ${C^*}_{th}$ the theoretical $C^*$ value [m/s]. The ${C^*}_{th}$ value was determined using the NASA CEA code and $\eta_{c^*}$ was estimated by Wada et al. [8]. The combustion chamber volume was determined using the L* value resulting from a 60-mm diameter motor test, and set as the same value. Figure 6 shows the results of the end-burning gas generator combustion tests. An ignition peak is observed as a result of the functioning of the small igniter, and no combustion oscillation was observed during GAP combustion. Figure 7 shows the relationship between the pressure and the linear burning rate of the 60-mm and 80-mm diameter motors. The 80-mm diameter motor was obtained close to the linear burning rate of the 60-mm diameter motor.

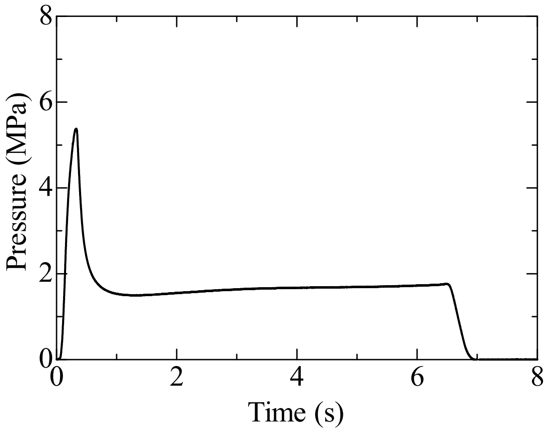

Figure 6: GAP gas generator pressure curve

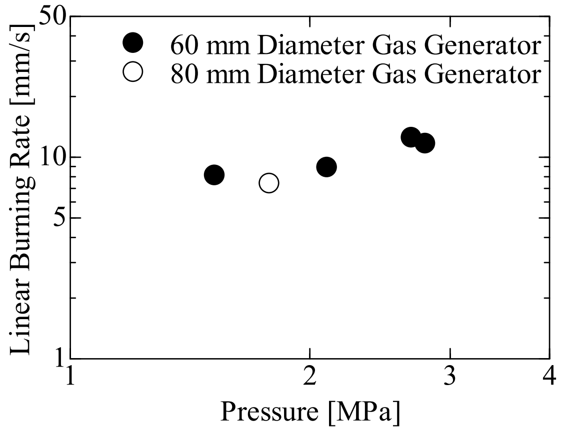

Figure 7: Relationship between pressure and linear burning rate

### 2.2 GAP direct-injection gas-hybrid rocket test with $N_2O$

The direct-injection gas-hybrid rocket was tested using a GAP gas generator loaded with $N_2O$. The combustion pressures were set to 2.5 MPa, and the $N_2O$ flow was adjusted based on the results of the gas-generator combustion test. The oxidizer feed-piping diagram is shown in Fig.8. Prior to ignition, the liquid $N_2O$ moved to the oxidizer tank from a high-pressure gas cylinder, and burned. Figure 9 shows photographs during the combustion of the direct-injection type gas-hybrid rocket motor, while Fig. 10 shows the chamber pressure curves measured for each test. Two experimental results are shown in Table 1. Ignition smoothness and combustion stability were observed. The supply of $N_2O$ gas was finished, after which the self-decomposition of GAP stopped. The case in (a) had low vapor pressure as a result of it having no adjustment to the temperature control. In the case in (b), the $N_2O$ vapor pressure was adjusted, and combustion pressure reached to 2.5 MPa. It was confirmed that no nozzle erosion occurred in both cases.

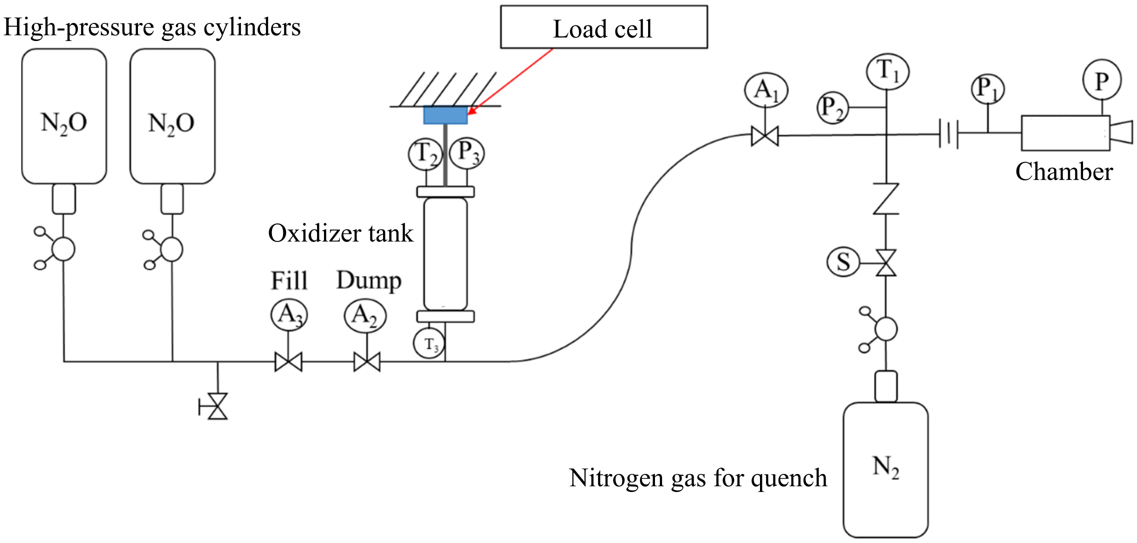

Figure 8: Piping diagram of $N_2O$ feed line from high-pressure gas cylinder to oxidizer tank.

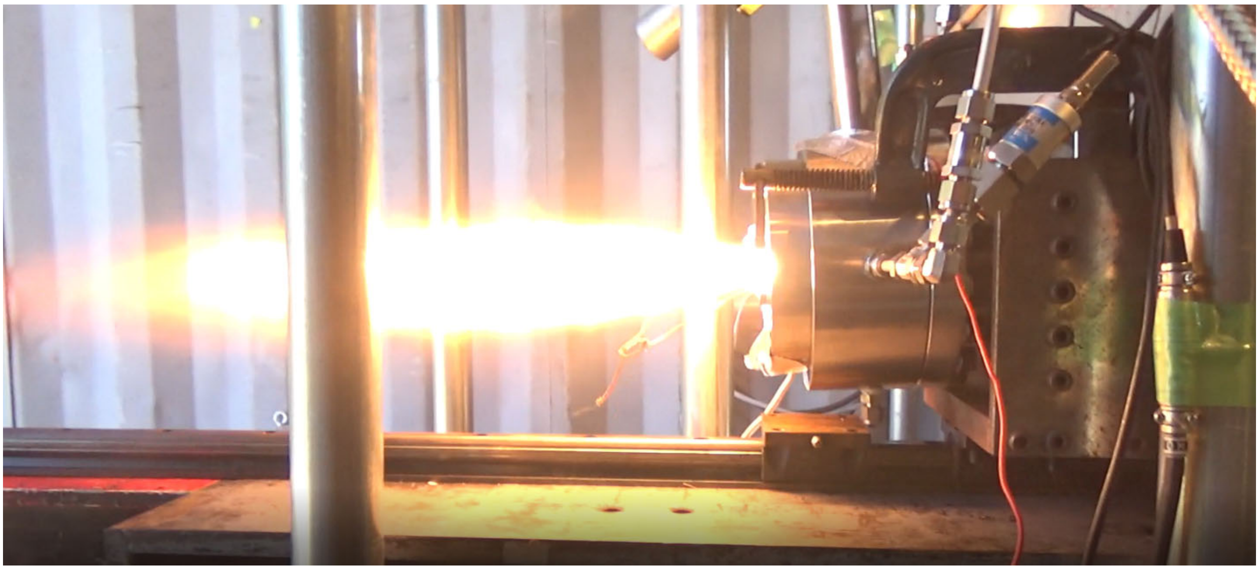

Figure 9: Firing test of direct-injection type gas-hybrid rocket

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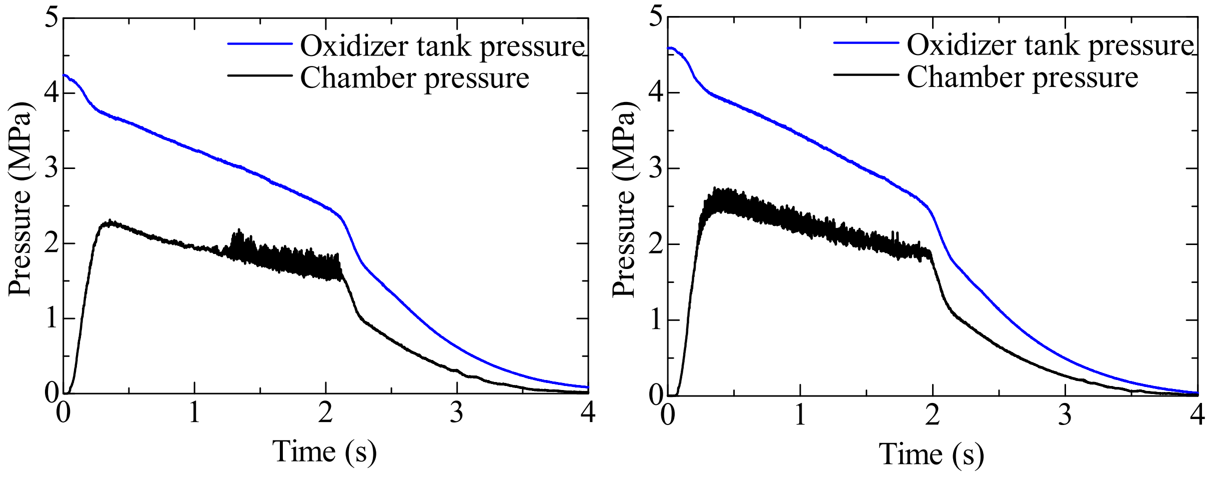

(a) (b)

Figure 10: Relationship between pressure and time for the two combustion results. (a) No. 1: Low $N_2O$ vapor pressure setup, (b) No. 2: High $N_2O$ vapor pressure setup.

Table 1: Results of the GAP/$N_2O$ gas hybrid rocket tests

| | **(a)** | **(b)** |
|---|---|---|
| Max pressure (MPa) | 2.32 | 2.50 |
| Average pressure (MPa) | 1.86 | 2.06 |
| Burning time (s) | 2.08 | 2.11 |
| Fuel burning rate (mm/s) | 9.74 | 12.06 |
| O/F (Opt.: 2.2) | 1.8 | 1.58 |
| C* (m/s) | 1388.5 | 1342.65 |
| C* efficiency (%) | 87.41 | 85.67 |

## 3. Discussion and conclusions

Nozzle erosion was observed in our previous study in which gas oxygen was used as an oxidizer, and the erosion rates were 0.275 and 0.378 mm/s. However, when $N_2O$ was used as the oxidizer, erosion was not observed because the O/F of both cases tended to the fuel-rich side. Figure 11 shows the relationship between the pressure and the GAP burning rate. The linear burning rates of the gas generator and hybrid combustion mode correspond to our previous results. The C* efficiency is shown in Fig.12. The GAP/$N_2O$ C* efficiency decreased compared to the GAP/GOX results. One of the reasons for this is the difference in motor size. The GAP/GOX experiment used the 60-mm diameter combustion chamber; however, the GAP/$N_2O$ experiment employed the 80-mm diameter combustion chamber in order to increase the thrust level for the small launching experiment. Another reason is the use of $N_2O$ as the oxidizer because the $N_2O$ feed is in the liquid state. Therefore, the increase in C* efficiency required an injector to promote atomization. In the second experiment, the oxidizer pressure was increased and the combustion pressure reached the target value. However, the linear burning rate of GAP also increased owing to the increase in combustion pressure, and as a result, the O/F value shifted the fuel-rich side. Therefore, a prediction of the linear burning rate of GAP with higher accuracy is required, and the result of the present the linear burning rate will be referred to in the next study.

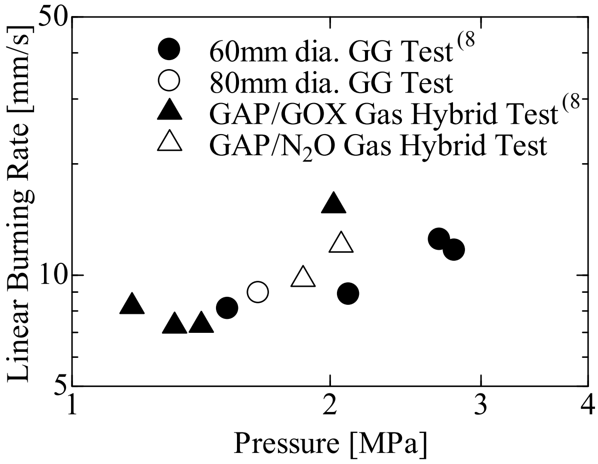

Figure 11: Relationship between linear burning rate and pressure.

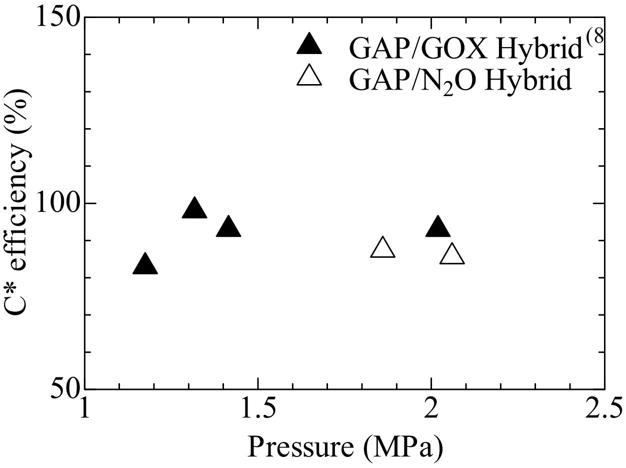

Figure 12: Relationship between C* efficiency and pressure

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