Research paper

Combustion characteristics of liquid GAP –Combustion products and *C** combustion efficiency–

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Abstract

We focused on Glycidyl Azide Polymer (GAP) as a next generation monopropellant that can be substituted for N_2H_4. GAP is one of the High Energy Materials (HEMs) and not so toxic compared with N_2H_4. However, it is known that GAP generates carbonaceous residues at its combustion. Combustion residues can cause low propulsion performance of a thruster. Therefore, when the combustion pressure was varied, we investigated the amount of combustion products from liquid GAP, and the influence that its combustion products give in its combustion characteristics. As a result, it was found that the amount of carbonaceous residues decreases from 30% to 20% and the C^* combustion efficiency becomes raised with increasing from 60% to 90% at a combustion pressure from 0.1 MPa to 1.0 MPa .

Keywords : monopropellants, liquid GAP, combustion residues, C^* combustion efficiency

1. Introduction

Satellites and other spacecraft use monopropellant thrusters to correct their trajectory or to control their attitude. Hydrazine (N_2H_4) has been used as a monopropellant for many years. N_2H_4 has high combusiton performance, and its thruster has high reliability with a simple design. However, N_2H_4 is toxic and hazardous to handle. It needs special precautions to protect people when handling it. Accordingly, monopropellants require higher propulsion performance and less toxicity.

We focused on Glycidyl Azide Polymer (GAP) as a next generation monopropellant that can be substituted for N_2H_4. GAP is one of the High Energy Materials (HEMs) which are focused upon for improving a propulsion performance of rockets[1]. Also, GAP is not so toxic compared with N_2H_4, and easy to handle[2].

Table 1 shows physicochemical properties of GAP[2), 9)]. The density and adiabatic flame temperature of GAP are higher.

However, it is known that GAP generates carbonaceous residues at its combustion[3), 4)]. Combustion residues can cause low propulsion performance of a thruster. Therefore it is desirable as a propellant not to generate combustion residues.

Table 1 Physicochemical properties of GAP.

Molecular weight [kg·mol^{-1}]	1.98
Density [kg·m^{-3}]	1.3×10^3
Heat of formation [kJ·kg^{-1}]	957
Adiabatic flame temperature [K]	1402 (at 1 MPa)
Main combustion products	N_2, C_{gr}, CO, H_2

The decomposition of GAP is closely related to an outbreak of combustion residues[3)–5)]. The decomposition model of GAP is shown in Figure 1. In the first step, N_2 is eliminated from the azide group. This reaction is the main decomposition of GAP and it emits a lot of heat.

In the second step, polyimine and polyacrylonitrile are generated after hydrogen (H_2) is eliminated. The third step is a separation of the main chains. After that, combustion products are finally generated. The elimination of H_2 in the second step is important in order for GAP to be completely decomposed. If H_2 isn't eliminated enough, the polymers generate carbonaceous residues. It is important to eliminate H_2.

Figure 2 shows a conception of a GAP thruster. Liquid GAP is pushed by high pressure gas, and injected to a combustor. Liquid GAP reacts in the combustor.

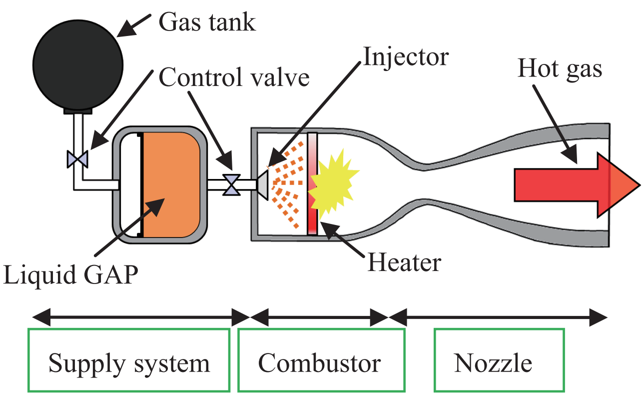

Figure 2 GAP thruster.

It is expected that the combustion pressure affects the combustion of GAP. Accordingly, it is necessary to investigate the amount of combustion products from liquid GAP, when the combustion pressure is changed.

Many researchers have studied GAP[6)-8)]. However, the carbonaceous residues generated from liquid GAP have not been mentioned very much. Furthermore, the influence that the products of liquid GAP give in a performance of the thruster has not been studied.

Therefore, we investigated following two things about liquid GAP, when the combustion pressure is varied.

- The amount of combustion products (H_2, carbonaceous residues) from liquid GAP.
- The influence that its combustion products give in its combustion characteristics.

2. Experiments

2.1 Amount of combustion products

The collection of H_2 and carbonaceous residues was performed with the experimental conditions shown in Table 2 and experimental apparatus shown in Figure 3. Liquid GAP obtained energy by heating element and started decomposition. Heating element explanation is shown in Table 3. The mass of liquid GAP increased to make detecting combustion products easy. Combustion pressure P_c and temperature T_c were measured synchronously by a pressure gauge and a thermocouple. The P_c was varied, as shown in Table 2. The H_2 produced was measured by detecting the combustion gas that led to a collection bag. The combustion residues were divided into carbonaceous residues and carbon graphite by using

Table 2 Experimental conditions 1.

Mass of GAP [g]	0.03 × 3
Combustion pressure [MPa]	0.1, 0.3, 0.6, 1.0
Initial temperature [K]	300
Ambient atmosphere	N_2
Gas analyzer type	Heat conduction

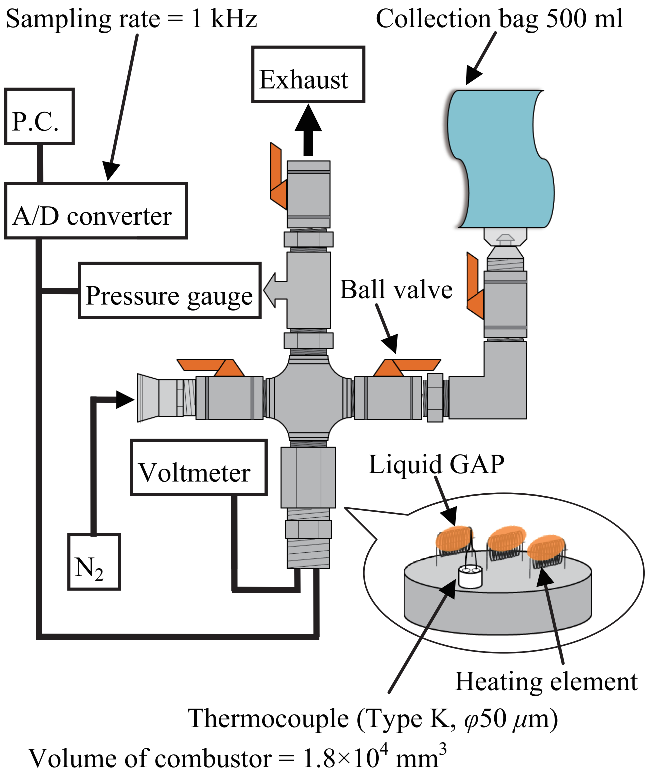

Figure 3 Experimental apparatus 1.

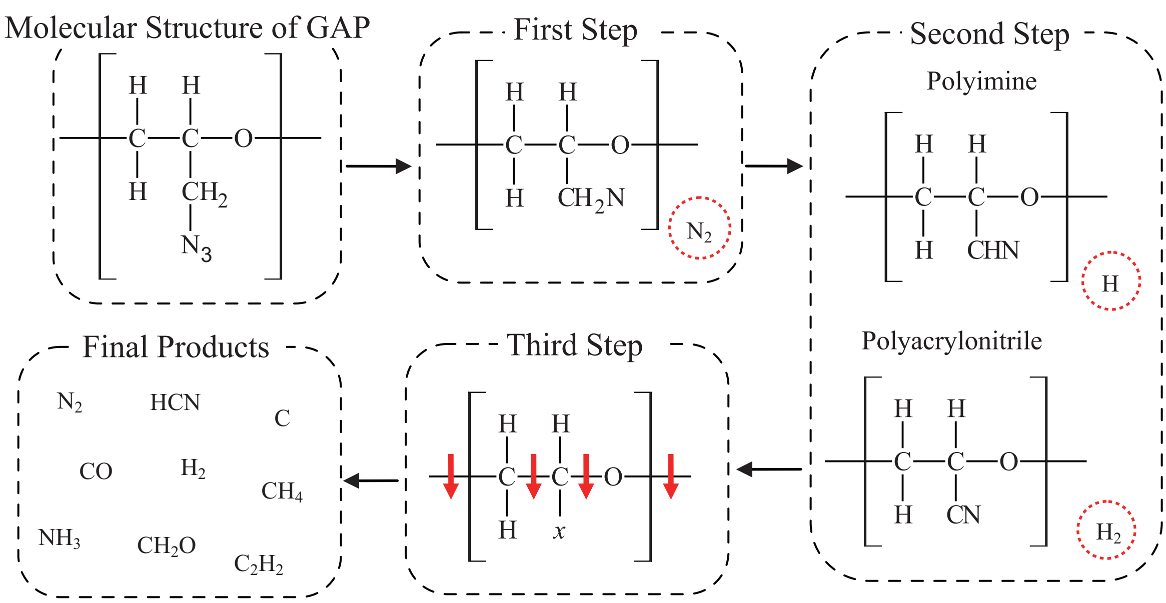

Figure 1 Decomposition model of GAP.

Table 3 Heating element.

Heater material	Nichrome wire
Wire diameter [mm]	0.23
Wire length [mm]	10
Resistance [Ω]	2.4
Applied voltage [V]	7

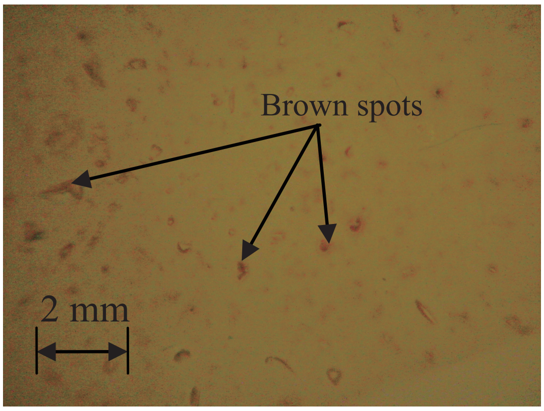

Figure 4 Carbonaceous residues.

methanol[3]. Figure 4 shows the carbonaceous residues. It is thought that brown spots have a big molecular weight.

2.2 C^* combustion efficiency

A micro thruster was used to obtain the C^* combustion efficiency of liquid GAP. The experimental conditions and experimental apparatus are shown in Table 4 and Figure 5. The measurement conditions were the same as the former experiment. The micro thruster was put into N_2 atmosphere and at 0.1 MPa. P_c was varied according to the difference of the nozzle throat area A_t, as shown in Table 4. Characteristic length L^* is explained as follows: $L^* = V_c/A_t$[10]. The V_c is a volume of combustor. In this experiment, the V_c was constant and the A_t was only varied.

3. Results and discussion

3.1 Amount of combustion products

Bubbles appear in the GAP droplet by heating from the heater. The GAP droplet became filled with a lot of micro bubbles in the GAP droplet. The GAP droplet micronized and became gas in a moment to increase internal pressure.

Figure 6 shows the relationship between the amount of H_2 produced n_{H2} and the combustion pressure P_c.

The relationship between the carbonaceous residue ratio η_r and the P_c is shown in Figure 7. The η_r is explained by Equation 2.

Table 4 Experimental conditions 2.

Mass of GAP [g]	0.06
Nozzle throat area [mm²]	6.6, 3.7, 1.75
Characteristic length [m]	0.85, 1.5, 3.2
Initial pressure [MPa]	0.1
Initial temperature [K]	300
Ambient atmosphere	N_2

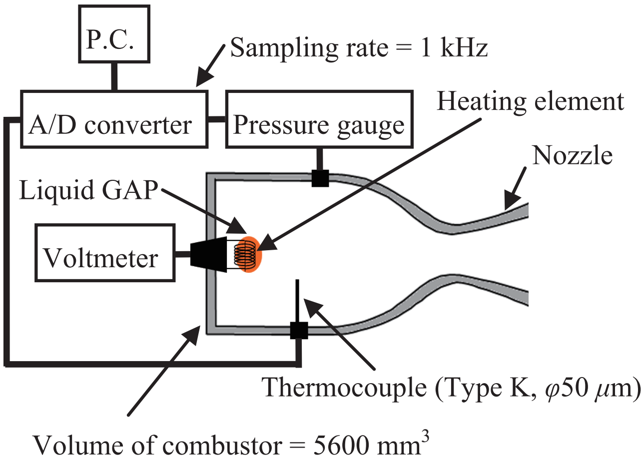

Figure 5 Experimental apparatus 2.

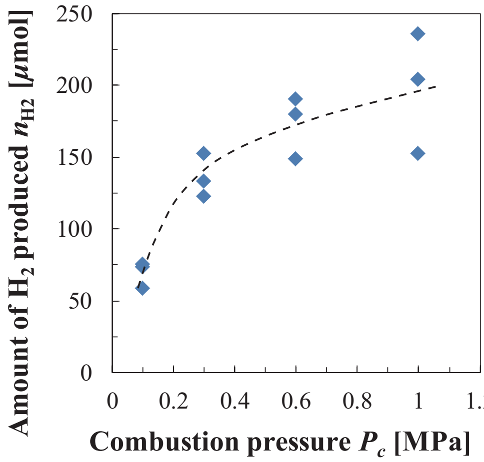

Figure 6 The relation between n_{H2} and P_c.

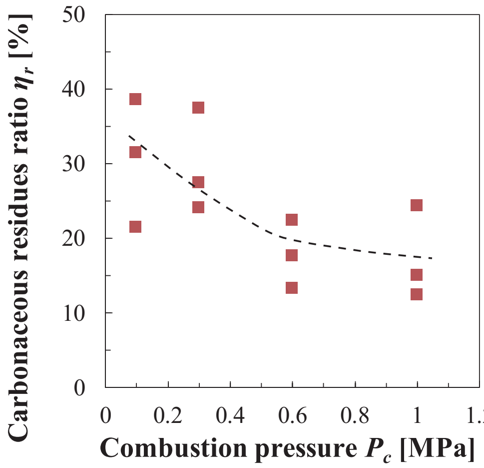

Figure 7 The relation between η_r and P_c.

$$\eta_r = \frac{m_r}{m_0} \times 100 \tag{2}$$

The m_r is mass of carbonaceous residues, and the m_0 is initial mass of liquid GAP.

The n_{H2} is raised and the η_r decreases with increasing the P_c. These mean that the decomposition of liquid GAP is promoted with increasing a pressure.

Generally, it is known that a decomposition velocity is mainly related to a temperature. The relation between the mean combustion temperature T_{cm} and the P_c is shown in

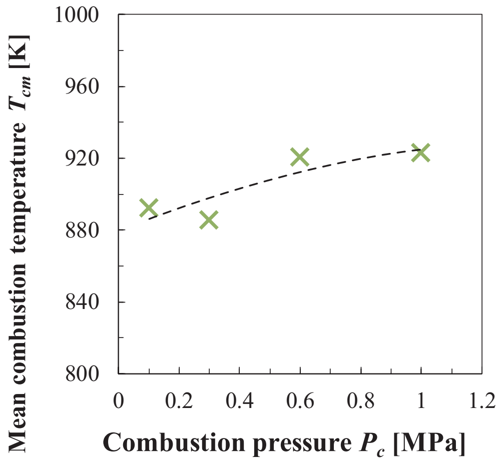

Figure 8 The relation between T_{cm} and P_c.

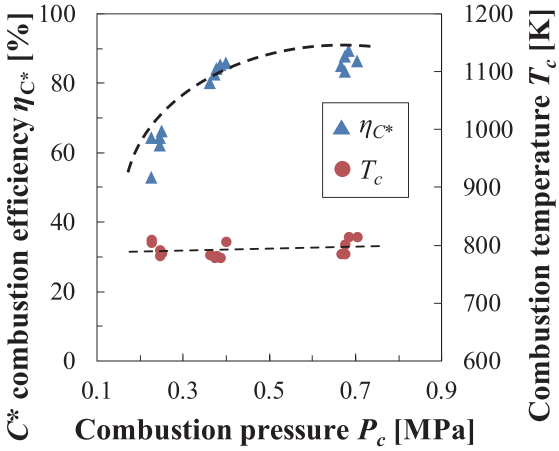

Figure 9 The relation between η_{C^*} and T_c.

Figure 8. The T_{cm} is slightly raised with increasing the P_c. From this result, it is considered that the decomposition of GAP is greatly affected by even a small rise of combustor temperature.

3.2 C^* combustion efficiency

The C^* combustion efficiency η_{C^*} is defined by Equation 3[10]. The C^*_{th} was calculated by using the NASA-CEA[9]. The C^*_{exp} was obtained by Equation 4[10].

$$\eta_{C^*} = \frac{C^*_{\mathrm{exp}}}{C^*_{th}} \times 100 \quad (3)$$

$$C^*_{\mathrm{exp}} = \frac{A_t P_c}{m_f} \quad (4)$$

The A_t is a nozzle throat area. The m_f is a mass flow rate of combustion gas.

Figure 10 shows the η_{C^*} and the T_c against varied the P_c for liquid GAP. The η_{C^*} of liquid GAP is raised with increasing the P_c. On the other hand, the T_c is almost constant. The η_{C^*} is proportional to a square root of T_c/M[10]. The M is the molecular weight of combustion gas. Therefore, it is considered that the cause of increasing the η_{C^*} is a decrease of the M. Also, the T_c is about 600 K lower than the adiabatic flame temperature. It is thought that the result is incomplete decomposition caused by carbonaceous residues.

4. Conclusion

In this study, we obtained the following conclusions.

- The amount of carbonaceous residues of liquid GAP decreases from 30% to 20% with increasing from 60% to 90% at a combustion pressure from 0.1 MPa to 1.0 MPa, because its decomposition is promoted.
- The C^* combustion efficiency of liquid GAP becomes raised with increasing the combustion pressure because the composition of combustion gas is changed.

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