A Study on Combustion Efficiency Improvement of Low Melting Temperature Thermoplastics as a Hybrid Rocket Fuel

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This paper introduces the development of laboratory scale hybrid rocket using low melting point thermoplastics (LT) as a hybrid rocket fuel. The LT developed by Katazen Corporation have the higher regression rate comparing with Hydroxyl-Terminated-PolyButadiene (HTPB) and excellent mechanical properties, which makes them as promising candidates for hybrid rocket fuel. Therefore, the small hybrid rocket motor of the LT was prepared for the rocket launch program of the space-education using N_2O as oxidizer. The motor length is variable and combustion efficiency was evaluated at several L/Ds. From the result was confirmed that characteristic exhaust velocity (C^*) was increased significantly with increasing of the characteristic length (L^*). From these results were suggested that the unburned fuel droplets did not contribute to combustion as a fuel. However, large L^* will become large motor and will cause low fuel volume density in the chamber. In this study, C^* function was investigated by static firing test using several types of baffle plate and several shape of aft combustion chamber as to small L^* and confirmed large increasing of C^* under the small L^* . The details are presented and discussed in this paper.

Key Words: Low Melting Point Thermoplastics, High Regression Rate Fuel, Hybrid Rocket

Nomenclature

G	: mass flux
r	: surface regression rate
C^*	: characteristic exhaust velocity
L^*	: characteristic length

Subscripts

ex	: experimental data
$theo$	: theoretical data

1. Introduction

Hybrid rockets are a type of chemical rocket propulsion system; they usually employ a liquid or gas oxidizer and solid fuel. Hybrid rockets have several benefits: throttability, environmentally friendly nature, simplicity, and low costs. Some of these benefits suggest that hybrid rockets would be excellent educational tools for students. In recent years, some Japanese students have launched small hybrid rockets as part of a space education activity¹⁾. The rocket was required to lift a 500 g payload beyond a height of 300 m. The thrust level was 300–500 N.

Students mainly use an amateur hobby system for hybrid rocket development; however, this system has many faults such as combustion instability, low thrust power, and unstable burning time. These disadvantages may cause low air speed immediately after a rocket launch and induce aerodynamic instability, which is dangerous. Therefore, this study focused

on developing a small hybrid rocket engine with high reliability and safety for space education.

Current hybrid rockets mainly use inert polymers such as hydroxyl-terminated polybutadiene (HTPB), polypropylene, and polyethylene as a solid fuel. HTPB was developed for solid fuel rockets. Research closely examined its adhesiveness with other materials and its combustion characteristics; it has also been successfully used as a fuel for hybrid rockets. However, conventional hybrid rockets have a defect in that the regression rate of the fuel is very slow because of the low-energetic polymer. Gasification of such fuels is promoted only by heat transfer from the boundary layer flame, which is one reason for the low regression rate of hybrid rocket fuels. Several research groups have promoted the gasification of fuel²⁾; the development of a new solid fuel with a high regression rate has also been studied. Hori and Kimura (1996)³⁾ examined a high-performance hybrid rocket using high-energetic polymers with a high regression rate as the solid fuel. They used glycidyl azide polymer (GAP). Because of its self-combustibility, GAP is a promising solid fuel for gas-generator-type hybrid rocket systems; these are also called gas hybrid rockets⁴⁾⁻⁸⁾.

Another approach has focused on low melting point materials as a new solid fuel for hybrid rockets. Low melting fuels have a different transfer mechanism and have a high regression rate compared with HTPB. For instance, wax and paraffin^{9), 10)} are typical low melting point fuels and

additionally have the benefit of low cost. These fuels have a thin liquid layer during combustion, and mechanical entrainment of the liquid droplets from the liquid surface is induced by upstream oxidizer flow. A high amount of entrainment of liquid droplets produces a high regression rate for the solid fuel. This phenomenon is called entrainment mass transfer mechanism. However, the poor mechanical properties and adhesion with other materials of wax and paraffin fuel may hamper the application of this material to full-sized rocket motors.

Therefore, this study focused on a thermoplastic polymer with a low melting point and excellent mechanical properties. Low melting point thermoplastics (LT) fuel has the potential for a high regression rate because it has similar physical properties as low melting point paraffin fuel. Katazen Corporation has developed LTs with excellent mechanical properties; they developed special LTs for this use and lowered the melting point down to the hot water temperature range. In the present study, several LTs were evaluated by measuring the regression rate under the low oxidizer mass flux region. Table 1 presents the LT fuel samples #1, #2, and #3; these melted at approximately 90 °C and could be molded into hollow circular cylinder samples for the experiments. Figure 1 shows each molded fuel sample in the acrylic pipe. Figure 2 shows the results of the regression rate. The fuel regression rates were higher than those of HTPB and PMMA fuel. However, the measurement region of the oxidizer mass flux was very narrow, so the regression rate had to be measured in the higher region.

Table 1. LT fuels.

Sample	Main component	Theoretical element ratio	Hardness
#1	Polystyrene	C 33% H 67% O 0% N 0%	Medium
#2	Stearic acid	C 33% H 67% O 9% N 1%	Hard
#3	Styrene	C 34% H 66% O 0.4% N 0%	Soft

Fig. 1. Each molded LT sample in an acrylic tube.

Fig. 2. Comparison of regression rates of each fuel.

Although #3 had the highest regression rate. Therefore, a uniaxial tensile test was carried out on #3. The sample broke at the parallel portion of the distance between the black markings, and there was little dispersion in the data. The photograph of a tensile test is shown in Fig. 3. The maximum strain for the test sample was over 300%; the elongation was better than that of conventional solid motor propellants.

Fig. 3. Test piece of #3 during tensile test.

These results showed that each LT fuel has good elongation; adequate true stress, better than that of conventional solid motor propellant; and high regression rates that are three to four times that of inert polymers. Of these fuels, #3 was selected because it had the best handling properties such as viscosity at service temperatures.

A small hybrid rocket using #3 was prepared for a space education rocket launch program with nitrous oxide (N_2O) as a liquid oxidizer. LT #3 was evaluated by measuring the regression rate and C^* under several lengths of chamber and baffle plate using N_2O . The effects of the oxidizer mass flow rate, chamber length, and baffle plate were evaluated, and the details are presented and discussed in this paper.

2. Experimental Section

2.1. Fuel samples

Thermoplastic is a polymer that turns to liquid when heated and to solid when cooled sufficiently; it differs from thermosetting polymers in that it can be remelted and easily remolded. Easy moldability is an advantage for solid fuels and helps reduce the manufacturing costs. Thermoplastics made by Katazen are elastic and flexible. This study used the styrene-based sample #3, which is hereafter referred to simply as “LT.”

2.2. Experimental setup

The small combustion chamber was made and used for the measurement of the surface regression rate. The schematic view of the $\phi 70\text{mm}$ diameter small combustion chamber is shown in Fig. 4.

Fig. 4. Schematic view of the small combustion chamber

The experimental setup for the oxygen gas type used a small flux of oxygen gas at the time of ignition; when a thin ignition fuel made from acrylics ignited, the oxygen gas flow flux was raised to a predetermined level, and nitrogen was supplied into the chamber immediately upon termination of combustion. The ignition energy was given by electronic spark energy. The mainstream oxygen line was controlled by a pneumatic driven ball valve, and the oxygen flow measurement used a sonic orifice whose coefficient of resistance was known. Strain gauge pressure sensors (Kyowa PGS-100kA) were used to measure the upstream pressure of the oxygen gas and the chamber pressure. In this study, the oxidizer mass flux and chamber pressure were varied between 5 and 80 $\text{kg}/(\text{m}^2\text{s})$ and 0.5 and 2.2 MPa, respectively, to examine the influence of the regression rate.

The experimental setup for the N_2O type used liquid N_2O as the oxidizer. Assembly of the liquid N_2O feed system and ignition system was based upon the Hyper TEK system (HyperTEK). N_2O is a self-pressurizing condensed gas that was stored within a 300 cm^3 aluminum oxidizer tank. As liquid N_2O was supplied to the combustion chamber during motor burn by the self-pressure, the tank pressure dropped owing to the dropping temperature for the heat of vaporization. Thus, the time history of the thrust profile also showed a declining trend. After the end of combustion, the combustion flame automatically extinguished. Measurement of the pressure in the N_2O tank and combustion chamber used the same equipment as for the oxygen gas type setup; the thrust

was measured by load cell sensors (Kyowa LMA-1kN). This study used four chamber lengths to investigate the combustion efficiency. Figure 5 shows several chamber lengths. Initial fuel port diameter is 25mm. Fuel lengths is 130mm and chamber lengths are 130mm, 200mm, 260mm, and 300mm as an after combustion region. Fuel cartridge is made from acrylics tube.

Fig. 5. Four types of chamber length

The baffle plate is shown in Fig.6 and has three holes which is 14.5mm diameter and 10mm thickness and made from carbon graphite. Total area of baffle plate hole was determined as same area as initial fuel port area.

Fig. 6. Shape of baffle plate

Figure 7 shows photograph of fuel cartridge with baffle plate and without.

Fig. 7. Fuel cartridge with baffle plate and without

3. Result and Discussion

Figures 8 and 9 shows the results from an representative test with oxygen gas and liquid N_2O as the oxidizer. Figure 8 shows that ignition was smooth and the chamber pressure rapidly rose to 2.6 MPa, after which the chamber pressure

soon decreased to near 2 MPa. The average oxidizer mass flow rate was approximately 40 g/s in this case. The oxidizer flow started at $t = 0$ s; the main oxidizer valve opened after 2–3 s; the oxidizer valves then closed, and the combustion was immediately terminated.

Fig. 8. Example of time histories for the pressure and oxidizer mass flow rate.

Fig. 9. Example of time histories for the pressure and thrust.

As shown in Fig. 9, the motor also showed good ignition performance when using the electrical spark wire; however, a large ignition peak was observed compared with the oxygen gas motor. This is because a large amount of gaseous fuel, where fuel gasification is driven by ignition energy, suddenly encountered liquid N_2O . The initial thrust also increased concurrently with the ignition peak; this is helpful for small rocket launches because the small rocket can then obtain enough flight velocity for attaining aeromechanical stability. The ignition peak of the chamber pressure was 4.5 MPa; the pressure then decreased to 3 MPa and then gradually decreased to 2 MPa. The average combustion pressure was 2.3 MPa, the largest thrust was 600 N, and the average thrust was 300 N. The motor capability was sufficient to launch the small hybrid rocket up to a height of 300 m.

Figure 10 shows the results for the LT fuel regression rate using oxygen gas and liquid N_2O as the oxidizer. The regression rate was calculated as an averaged value from the mass differences for the firing test before and after the experiment. After the firing test, the LT fuel melted slightly and accumulated at the bottom of the chamber; therefore, direct inside diameter measurement was omitted. The inside diameter after combustion was calculated from the mass difference, and the oxidizer mass flux was calculated as the

average oxidizer mass flux from the average inside diameter before and after the experiment.

Fig. 10. Comparison of regression rates for LT fuel and classical hybrid fuel.

The LT/GOX average regression rate is shown in the following equation:

$$\bar{r} = 0.137 \bar{G}^{0.54} \quad (1)$$

The average regression rate was in millimeters per second, and the average mass flux was in kilograms per square meter per second. The mass flux exponent was 0.54, which is less than the mass flux exponent of paraffin-based fuel⁹⁾ and classical fuel HTPB. The low mass flux exponent is expected to reduce motor performance shift due to the O/F-shift during the motor burn. The LT/GOX fuel average regression rate was also two to three times that of the classical fuel HTPB and was the same or slightly less than that of paraffin-based fuel. The LT/ N_2O average regression rate seemed to be of the same pressure exponent as the LT/GOX average regression rate. These results mean that the regression rate of hybrid rocket fuels does not depend on the type of oxidizer. The regression rate was confirmed to be dominated by droplets that were carried away by the oxidizer mass flux from the fuel surface by the entrainment effect¹¹⁾; the results of the fuel regression rate were independent of the type of oxidizer.

Figure 11 shows comparison of exhaust flame by the effect of baffle plate. Both of case coincide chamber length and L^* . It seems that the baffle plate contributes stability of exhaust flame and it may serve to increasing of combustion efficiency.

(a) Without baffle plate

(b) With baffle plate

Fig. 11. Comparison of exhaust flame.

Figure 12 shows experimental data of chamber pressure with baffle plate. These pressure data were observed at upper and down position of baffle plate. In this case is confirmed pressure drop less than 0.2MPa by the set of baffle plate. The value of pressure drop is satisfactory result because of small value compared to maximum pressure.

Fig. 12. Chamber pressure comparison

The C^* was observed at each static firing test and compared to theoretical performance of HTPB because detail structure of LT fuel such as heat of formation was classified shown in Fig.13.

Fig. 13. Experimental results of $\eta_{C^*_{LT}/HTPB}$

The $\eta_{C^*_{LT}/HTPB}$ is divided LT experimental C^* by theoretical data of HTPB. This $\eta_{C^*_{LT}/HTPB}$ evaluates the performance of a baffle plate in this study, and it differs from usual η_{C^*} . The η_{C^*} is also increasing both of data with the increase in L^* and increased approximately 1.3 to 3 times with the baffle plate. These results suggested that the baffle plate is effective of increasing C^* of LT fuel. The reason is as following; 1) residence time of combustion gas in the chamber is increased by recirculation region after baffle plate, 2) atomization of LT fuel droplet is furthered by same mechanism as other liquefied fuels such as wax fuel¹²⁾, and 3) gasification of LT fuel droplet is expected because the baffle plate is heating to high temperature by combustion flame.

4. Summary

Two types of hybrid rocket motors using oxygen gas and N_2O as the oxidizer were used to investigate the regression rate of LT fuel. Styrene-based LT fuel was selected as the main fuel because it had the best handling properties such as viscosity at service temperatures. The LT hybrid motor capability was adequate for launching a small hybrid rocket up to a height of 300 m in the N_2O experiment. The regression rates using oxygen gas and N_2O were compared. The LT/GOX regression rate was described by a regression curve of the oxidizer mass flux with an exponent of 0.54. The regression rate was two to three times higher than that of classical fuel for the hybrid rocket. The results suggest that the LT fuel has the same combustion mechanism as paraffin-based fuel because of its own low melting temperature. Therefore, LT fuel is a good candidate for hybrid rocket fuels as it has excellent mechanical properties and a high regression rate. The baffle plate improved C^* efficiency especially at small L^* region. And this result has suggested a possibility that the volume of LT fuel chamber can be decreased.

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