Experimental Investigation of Fuel Regression Rate of Low-Melting-Point Thermoplastic Fuels in the Altering-Intensity Swirling-Oxidizer-Flow-Type Hybrid Rocket Engine

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In this study, we developed a high-performance and high-thrust hybrid rocket motor using low-melting-point thermoplastic (LT) fuel and swirling oxidizer flow. LT fuel has excellent mechanical and adhesive properties, as well as a high regression rate compared to conventional hybrid rocket fuel. In this study, we conducted several firing tests using swirling oxidizer flow to obtain the fuel regression rate and evaluate its effects on the geometric swirl number (S_g). We determined that the average regression rate of the LT fuel with $S_g = 37.3$ was ~2.9 times larger than the axial flow test value. The LT fuel was more susceptible to swirling flow than polypropylene, presumably due to the different physical properties of the fuels. In the swirl flow experiment, we confirmed that the local fuel regression rate behind the fuel is uniform, and it differs from the regression rate seen in the axial flow experiment. For the range of oxygen mass flux values $G_{oxlo} = 30 - 72$, $\dot{r}_{loave}$ was fitted to a conventional formula. The results of this fit suggested that the local regression rate at the head region of low-melting-point fuel, such as the LT fuel, cannot be represented only by chemical reactions; therefore, the fluid dynamics of liquefied fuel must be included in the model.

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

Nomenclature

D_{fport}	: fuel initial port diameter [mm]
D_t	: initial nozzle throat diameter [mm]
G_{ox}	: oxygen mass flux [kg/m ² s]
G_{oxlo}	: average local oxygen mass flux [kg/m ² s]
L_f	: fuel length [mm]
$\dot{m}_{ox}$	: oxidizer mass flow rate [g/s]
P_c	: combustion chamber pressure [MPa]
P_{ox}	: oxidizer pressure of upper orifice [MPa]
R	: moment arm [m]
R^2	: determination coefficient
$\dot{r}$	: fuel regression rate [mm/s]
$\dot{r}_{lo}$	: local fuel regression rate [mm/s]
$\dot{r}_{loave}$	: average local fuel regression rate [mm/s]
S_g	: geometric swirl number
T_b	: burning time [sec]
$u_{\theta ox}$	: tangential oxidizer velocity [m/s]
u_{xox}	: axial oxidizer velocity [m/s]

1. Introduction

The hybrid rocket is a type of chemical rocket propulsion system, and generally utilizes a liquid or gas oxidizer and solid fuel. Hybrid rockets offer several benefits; they are environmentally-friendly, safe, and inexpensive. Conventional

types of hybrid rocket primarily utilize inert polymers, such as hydroxyl terminal polybutadiene (HTPB), as a solid fuel. HTPB was developed for use as a solid rocket fuel binder, and its adhesive and combustion characteristics are well-studied. However, these polymers have a very low fuel regression rate, which is problematic in the development of large hybrid rocket motors. The gasification rate of solid fuels is determined only by the amount of heat transfer from the boundary layer flame, which is a reason for the low regression rate of hybrid rocket fuels. Therefore, extending the combustion surface area to increase the fuel mass flow rate would enable the generation of higher thrust.

Two approaches have been studied to improve the low fuel regression rate of conventional hybrid rocket fuels. The swirling flow of oxygen is an approach that has been shown to increase fuel regression rates, as reported by Yuasa et al.¹⁾ The other approach involves the development of low-melting-point fuel. Low-melting-point fuels, such as paraffin, have higher regression rates than HTPB.²⁾ However, poor mechanical and adhesive properties of the paraffin fuel hamper its application in full-sized hybrid rocket motors.

Therefore, our study focused on a low-melting-point thermoplastic (LT) fuel made by *Katazen Corporation*, Japan. This LT fuel had a high regression rate (comparable to paraffin fuel) and excellent mechanical properties.³⁾ One study demonstrated that LT fuels have maximum elongations of

greater than 300% and better adhesive properties with ethylene propylene diene monomer (M-class) rubber.⁴⁾ Combustion of the LT fuel has been confirmed in an in-flight environment.⁵⁾ The characteristic velocity efficiency of the LT fuel was improved by using a baffle plate.⁶⁾ These properties suggest that LT fuel can be applied in large hybrid rocket engines.

Nevertheless, the hybrid rocket system has an “O/F shift” problem arising from the changes in oxidizer mass flux during thrust throttling due to an increased burning surface area. Therefore, optimizing hybrid rocket performances such as specific impulse and characteristic velocity efficiency is challenging. A hybrid rocket research working group in *ISAS/JAXA*, Japan proposed the use of the Altering-intensity Swirling-Oxidizer-Flow-Type (A-SOFT) Hybrid Rocket Engine (HRE) to solve this problem. The system concept involves optimizing O/F during combustion by utilizing two oxidizer flow lines. One of these oxidizer flow lines is oriented axially, and the other is oriented tangentially to the motor. This configuration enables the control of the axial-to-tangential injection flow ratio and the oxidizer mass flow rate independently.⁷⁾ The oxidizer mass flow rate and swirling flow intensity are controlled by two flow lines, the fuel regression rate is controlled by above two functions, and O/F is set to the optimal value. In simulations, thrust- and O/F- controllable engines showed higher performance at every target altitude level. The research concluded that O/F-controlled hybrid rocket engines have wider ranges of compatibility with various types of thrust profiles than O/F-uncontrolled hybrid rockets.⁸⁾ A-SOFT HRE combustion experiments have been conducted using a conventional plastic fuel.⁹⁾

In this study, we investigated the LT fuel regression rate of swirling oxidizer flow in an A-SOFT HRE. This paper shows static firing test results and compares the regression rate of the axial oxidizer feed to the regression rate of the swirling oxidizer ($S_g = 37.3$).

2. Mechanical Properties of the LT Fuel

LT fuels can be classified into several types according to their material components. Table 1 lists the physical properties of the LT fuel used in this study. The base resin is a polystyrene elastomer, and paraffin oil is added as a low-melting-point oil. The xylene resin is added to improve adhesion. The maximum elongation of this sample is ~500%, which is better than that of conventional solid rocket propellants. The maximum adhesive stress of the LT sample is ~0.5 MPa.⁴⁾

Table 1. Properties of LT fuel.

Base resin	Polystyrene elastomer
Low-melting-point oil	Paraffin oil
Adhesive resin	Xylene resin
Density [g/cm ³]	0.92
Elastic modulus [MPa]	0.26
Maximum elongation [%]	499.8
Softening temperature [°C]	About 65
Viscosity at 100 °C [Pa · s]	2.85
Casting temperature [°C]	120

3. Experimental Setup

3.1. Test motor

Figure 1 shows the cross-section view of the test motor. The test motor was oriented horizontally in the test stand as shown in Fig. 2. The total length of the motor was 475 mm, combustion area length was 330 mm, and outermost diameter was 190 mm, and the inner diameter of the chamber was 100 mm. All components of this motor were made of SUS304 stainless steel, the fuel cartridge was made of polymethyl methacrylate (PMMA), the insulator was made of Bakelite resin, and the nozzle was made of graphite. The initial nozzle diameters for each experimental condition are shown in Table 3. The oxidizer was supplied from the axial feed line. In the swirl flow test, the oxidizer was supplied from the tangential feed line. The LT fuel, which was casted in a PMMA cartridge, was set in a chamber, and both of sides of the LT fuel were restricted by epoxy resin. Figure 3 shows the two types of injectors. The geometric swirl number was calculated using Eq. (1), and equaled 37.3.

Fig. 1. Cross-section view of the test motor.

Fig. 2. Schematic view of the test stand.

Fig. 3. Two types of injectors.

$$S_g \equiv \frac{\text{Angular momentum flux}}{\text{Axial momentum flux} \cdot \text{Radius}} \cong \frac{\dot{m}_{ox} u_{\theta ox} R}{\dot{m}_{ox} u_{x ox} R} = \frac{u_{\theta ox}}{u_{x ox}} \quad (1)$$

3.2. Oxidizer feed, measurement and control system

The feed system diagram is shown in Fig. 4. Gaseous oxygen (GOX) was used as oxidizer. The mainstream oxygen flow was controlled by an air actuator valve, and the GOX mass flow rate was regulated by a choked orifice. The GOX mass flow rate was measured by the Coriolis mass flow meter. The maximum GOX flow rate of this system was approximately 140 g/s. Strain gauge pressure sensors (KYOWA PGS series) were used to measure all pressures. An electronic spark wire was used for ignition. The axial and tangential feed lines are shown as dotted and dashed lines in Fig. 4. Only the axial feed line was used in the axial-flow test, while only the tangential feed line was used in the tangential-flow test. LabVIEW software was used for all measurements and valve controls.

Fig. 4. The GOX feed system diagram.

3.3. Operation sequence

Table 2 presents an example of an operation sequence used in the static firing tests. A small amount of GOX for ignition was supplied at T-13 seconds. The igniter was started 3 seconds before the main valve was opened. The main valve opening time was between 2.5 to 5 seconds, depending on individual test conditions. The N₂ purge valve opened for 60 seconds beginning 1 second after the main valve closed.

Table 2. Example of a time sequence.

Time [sec]	Item
T-20	Sequence and measurement start
T-18	Emergency valve open
T-13	GOX for ignition valve open
T-3	Igniter ON
T±0	Main valve open, Igniter OFF
T+1	GOX for ignition valve close
T+5	Main valve and emergency valve close
T+6	N ₂ purge valve open
T+66	N ₂ purge valve close
T+70	Sequence and measurement stop

3.4. Experimental conditions

The parameters used in each experiment are listed in Table 3. Experiments #1 through #4 were axial burning tests ($S_g = 0$), and experiments #5 to #9 were swirl oxidizer tests ($S_g = 37.3$). The burning time was determined by the oxidizer mass flux. Three fuel lengths of 80, 200, 330 mm were used, and were set to achieve the same value of O/F for each experiment. The targeted chamber pressure was either 2.0 or 3.0 MPa. The initial diameter of fuel port was 40 mm; however, the fuel port diameter of experiment #2 was 47.5 mm, because the fuel was reused after experiment #1. The initial nozzle throat diameter was determined using the targeted chamber pressure. Targeted GOX mass flux was set to values between 30 and 90 kg/m²s. The measured parameters are listed in Table 3.

4. Results and Discussion

4.1. Overview of static firing test

An example of test results obtained from the static firing test is shown in Fig. 5. All experiments show that ignition was smooth, and stable combustion was observed. The chamber pressure plotted in Fig. 5 (b) decreased due to nozzle erosion. Nozzle erosion was observed in experiments #3, #7, #8, and #9. The experimental conditions of these tests involved GOX mass fluxes over 50 kg/m²s.

(a) Experiment #4: axial flow test
($T_b = 5.72$, $P_{ox} = 5.15$, $P_c = 2.70$, $\dot{m}_{ox} = 125$)

(b) Experiment #9: swirling flow test
($T_b = 3.20$, $P_{ox} = 5.91$, $P_c = 2.98$, $\dot{m}_{ox} = 137$)

Fig. 5. Time histories of pressure and GOX flow rate.

4.2. Regression rate

Figure 6 shows the fuel regression rate of the LT fuel and polypropylene (PP) fuel. The fuel regression rate of the LT fuel was calculated from the mass difference before and after the firing test. Values of PP fuel data were obtained from a study conducted by Ozawa,¹⁰⁾ in which they used the same motor as in this study. The regression rate of the LT fuel with $S_g = 0$ was comparable to the value obtained from PP fuel with $S_g = 37.3$. The regression rate of the LT fuel with $S_g = 37.3$ was approximately 2.9 times larger than the rate obtained via axial flow tests.

The fuel regression rate of LT/GOX are shown in Eqs. (2) and (3).

$$\dot{r}|_{S_g=0} = 0.048 G_{ox}^{0.709} \quad (2)$$

$$\dot{r}|_{S_g=37.3} = 0.103 G_{ox}^{0.786} \quad (3)$$

The regression rates of the LT fuel were dependent upon the oxidizer mass flux. The exponents on G_{ox} of 0.709 and 0.786 were close to the exponent value of the conventional fuel, 0.8, which is based on diffusion-limited boundary layer combustion.¹¹⁾ This suggests that the reaction of the LT fuel was diffusion-limited. The regression rate of the PP fuel with $S_g = 37.3$ was approximately twice that of the PP fuel with $S_g = 0$. The increase rate of the regression rate of the PP fuel under swirling flow was less than the LT fuel.

In the swirling flow, swirling action in the radial direction promotes the thermochemical reaction, thereby accelerating the fuel retraction speed of the leading-edge. This is because the swirling oxidizer flow decreases the boundary layer thickness and improves the turbulent heat transfer by causing an increase in the local velocity near the fuel surface. In the rear of the fuel, the developing turbulent boundary layer shifts to become developed turbulent pipe flow. Therefore, it is expected that the fuel regression rate behind the fuel will be uniform. In a previous study, it was shown that low-melting-point fuel, such as LT fuel, liquefied on the fuel surface and flowed downstream due to the oxidizer flow.¹²⁾ This improves the fuel regression rate of the low-melting-point fuel. Applying a swirling flow to a low melting point fuel, it is possible that strong radial motion promotes the transportation of liquefied fuel.

Table 3. Parameters of each experimental condition.

Experiment #	1	2	3	4	5	6	7	8	9
GOX flow type	Axial ($S_g = 0$)				Swirl ($S_g = 37.3$)				
T_b [sec]	5.0		5.5		3.0	5.0	5.5	3.5	3.0
L_f [mm]	200		330		80		200		
P_c [MPa]	2.0	2.0	2.0	3.0	2.0	2.0	3.0	3.0	3.0
Initial D_{fport} [mm]	40.0	47.5	40.0						
Initial D_t [mm]	8.3	10.1	9.5	10.6	8.4	10.3	11.0	11.7	12.5
G_{ox} [kg/m ² s]	30	40	70	86	30	40	58	64	70
Measurement item	• Oxidizer pressure of upper orifice • GOX mass flow rate				• Temperature of upper orifice • Temperature of outside of nozzle insulator		• Chamber pressure

Fig. 6. Fuel regression rate of LT fuel and PP fuel.¹⁰⁾

4.3. Fuel surface and local regression rate

Photographs of the fuel surface after combustion are shown in Fig. 7. These are detached LT fuel materials from the PMMA cartridge, cut at one position on the circumference, and spread out into a plane. Oxidizer flows from the upper edge of the photograph to the bottom, nozzle-side edge of the photograph. In Fig. 7 (a), only the rear of the fuel has soot because the low viscosity fuel of the upper side was exposed to an N₂ purge after combustion. Oblique waves and roughness were formed, as shown in Fig. 7 (b).

(a) Surface of LT fuel after experiment #4

Fig. 7. Burnt surface after the static firing test.

(b) Surface of LT fuel after experiment #9

Fig. 7. Burnt surface after the static firing test.

Section views of the LT fuel after axial and swirling flow tests (#2 and #9, respectively) are shown in Fig. 8. Figure 9 shows the local regression rates of the LT fuel at $S_g = 0$ and $S_g = 37.3$. These local regression rates were obtained via image analysis of the LT fuel cross sections, which measured the average thickness of 12 sections, and divided the difference from the initial port diameter by the burning time. The local regression rate was greatest at approximately 10 mm from the leading edge of the fuel. We suspect that at the fuel's leading edge, the momentum of the oxidizer in the radial direction and the high oxygen concentration bring the boundary layer flame closer to the fuel surface. The $\dot{r}_{lo}$ in the axial flow decreases gently, whereas in the swirling flow it is nearly constant.

(a) Section view of LT fuel after experiment #2

(b) Section view of LT fuel after experiment #9

Fig. 8. Examples of section views of LT fuel after static firing tests.

(a) Results of axial flow tests ($S_g = 0$)

Fig. 9. Time-averaged local fuel regression rate of the LT fuel.

(b) Results of swirling flow tests ($S_g = 37.3$)

Fig. 9. Time-averaged local fuel regression rate of the LT fuel.

To investigate the influence of swirling flow on the local regression rate, the $\dot{r}_{lo}$ was divided into head and rear regions based upon the point where the $\dot{r}_{lo}$ and averaged overall $\dot{r}_{lo}$ intersected, as shown in Fig. 10. The relationship between the local oxygen mass flux, G_{oxlo} , and the local averaged fuel regression rate, $\dot{r}_{loave}$, in each region is shown in Fig. 11. The $\dot{r}_{loave}$ values for $G_{oxlo} = 30 - 72$ were fitted to an exponential function. The exponent value obtained from the fit at the head region was 1.033, which is high compared to the exponent typically obtained in boundary layer combustion experiments. This suggests that the liquefied fuel at the head region was transported backward by the swirling motion. It is suggested that the $\dot{r}_{loave|head\ region}$ of low-melting-point fuels, such as the LT fuel, cannot be determined by using only chemical reaction equations; therefore, the fluid dynamics of liquefied fuel must also be considered.

Fig. 10. Example of local regression rate of head and rear regions.

Fig. 11. The relationship between the local oxygen mass flux and the local averaged fuel regression rate.

5. Conclusion

Combustion experiments were conducted to investigate the influence of swirling oxidizer flow on the fuel regression rate of LT fuel. The following results were found:

1. Stable burning was confirmed in the swirling oxidizer flow tests.
2. The average regression rate of LT fuel with $S_g = 37.3$ was ~ 2.9 times the value obtained in axial flow tests.
3. LT fuel was more susceptible to swirling flow than PP fuel, which is presumably due to the differences in

physical properties between the fuels.

4. The local regression rate was the greatest ~10 mm from the leading edge of the fuel.
5. In the swirl flow experiment, it was confirmed that the local fuel regression rate was uniform behind the fuel, and clearly differed from the result of the axial flow experiment.
6. It is thought that the turbulent boundary layer developed due to the swirling flow and shifted to turbulent pipe flow at an early stage.
7. For $G_{oxlo} = 30 - 72$, $\dot{r}_{loave}$ was fitted to a conventional formula. This fit suggested that the local regression rate at the head region of low-melting-point fuels, such as the LT fuel, cannot be modeled only by chemical reactions equations; therefore, the fluid dynamics of liquefied fuel must also be considered.
8. Conclusions numbered 1, 2, 3, and 5 suggest that the A-SOFT HRE using the LT fuel can control thrust levels at a wider range of values than when using PP fuel. Moreover, we expect that the amount of LT fuel residue may be less than the amount of residue left by PP fuel.

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