Development of a Candy Hybrid Rocket Motor for Undergraduate Space Education

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In this study, a reusable educational motor that can burn different types of materials in the chamber was developed. Specifically, five candidate sweets were selected as fuel and burnt. The combustion performances of these sweets were compared, and the soft candy was selected as the solid fuel to be used in the motor, because it had the highest total impulse. The SOUKI Systems Co. Ltd. designed a small candy hybrid rocket based on these results. The candy rocket was launched successfully using soft candy at the Kada Cosmo Park. The motor carried the candy rocket to 319 m altitude and was fully functional under the high-acceleration environment.

Key Words: Hybrid Rocket, Fuel, Combustion, Launching Experiment, Space Education, Candy Rocket Project

1. Introduction

A hybrid rocket propulsion system is known for its non-explosive propulsion that is achieved because the inert polymer acting as the solid fuel and the liquid oxidizer are separately stored. A massive hybrid rocket system has never been implemented owing to the low thrust, primarily resulting from the low fuel regression rate. Therefore, some high-regression rate fuels and effective combustion techniques are being proposed by several researchers.¹⁻⁸⁾ However, hybrid rockets have numerous advantages: throttability, environmentally friendly nature, simplicity, and low cost. Based on these characteristics, hybrid rockets are expected to be excellent educational tools for undergraduate students. A small hybrid rocket has already developed under the rocket launch program of the undergraduate space education at several university in Japan, and the program have been launching the rocket using the HyperTEK⁹⁾ system, manufactured by Cesaroni Technology Inc. in Canada, every August during the Noshiro Space Event held in the Akita prefecture and every March during the Oshima Space Event organized in Tokyo. The HyperTEK system is highly safe and useful as a large thrust generation system in comparison with other educational rocket motors. It utilizes Acrylonitrile-styrene-acrylate (ABS) resin as the solid fuel and liquid N₂O as the oxidizer. The fuel grain is a disposable system. For performing numerous experiments, it is necessary to prepare the fuel grains for each experiment. However, this system is not suitable for learning rocket propulsion engineering because students can only be users of this engine.

One of the benefits of a hybrid rocket is that a wide range of

high-calorie solid materials can be selected as the fuel. Therefore, in this study, we developed a new hybrid rocket motor that can be used with several solid materials as the hybrid rocket fuel, and applied it as a motor for the education of high school and undergraduate students. The detailed results of the development of the educational motor, combustion tests, and launch experiment are reported in this paper.

2. Motor Development

2.1. Rocket motor case

Figure 1 shows a schematic of HyperTEK fuel grain and our proposed hybrid rocket motor. Table 1 compares our educational motor and the HyperTEK fuel grain. The HyperTEK fuel grain motor is made of ABS resin. Though the HyperTEK motor has been designed as a highly simple, lightweight system, it cannot be reused because its inside wall is burned directly as fuel by the oxidizer. In this study, we selected liquid N₂O as the oxidizer on account of its high vapor pressure at room temperature, which is useful for pressurizing gas.

The educational motor has a length of 339 mm, an outer diameter of 82 mm, and an inner diameter of 50 mm. The motor has a burning region, which has a larger volume than the HyperTEK system, for burning different types of fuels. The motor case is made of aluminum, and it can be reused. The baffle plate, made of polymethyl methacrylate (PMMA), is set inside the chamber to trap and hold the fuel grain at the front of the burning region and for increasing combustion efficiency. The ignition fuel is in the outer periphery of the combustion chamber, and a spark wire is used for ignition. A low melting temperature point fuel (LT fuel) was chosen as the ignition fuel

to have a high regression rate and excellent ignition.

The experimental conditions of our motor are listed in Table 2.

Fig. 1. (a) HyperTEK fuel grain motor, (b) schematic view of our hybrid rocket motor.

Table 1. Comparison of our hybrid rocket motor and the HyperTEK fuel grain motor.

Unit: mm	Original motor case	HyperTEK fuel grain
Length	339	285
Outer diameter	82	50
Inner diameter	50	25

Table 2. Experimental conditions of our hybrid rocket motor.

Burn time (s)	3
Combustion pressure (MPa)	2.5
Oxidizer mass flux ($\text{kg/m}^2 \cdot \text{s}$)	70
Measurement items	Oxidizer pressure Combustion pressure Thrust Video recoding

2.2. Fuel

In hybrid rockets, resin, rubber, or wax is typically used as solid fuel. Additionally, this educational motor is able to use several hydrocarbon-based materials as fuel in the burning region. In this study, various sweets rich in sucrose were selected as fuels. Figure 2 shows the theoretical performance of specific impulse (Isp) at sea level with sucrose and N_2O under the NASA chemical equilibrium with applications (CEA) program. The fuel performance of Hydroxyl-terminated polybutadiene (HTPB), a solid rocket propellant, is also shown for comparison in Fig. 2. Sucrose, which has the chemical formula $\text{C}_{12}\text{H}_{22}\text{O}_{11}$, has a higher oxygen content than HTPB. Therefore, the performance of sucrose is lower than of HTPB. To obtain high rocket performance by using sucrose fuel, a large amount of fuel gas is necessary.

Fig. 2. Comparison of the Isp (sea level) performances for sucrose and HTPB (Combustion pressure: 3 MPa) as fuels.

The sucrose based sweets used as the fuel in this study are listed in Table 3. It can be seen that sweets from several foreign countries are selected. The mass of each type of fuel in the combustion chamber was 64 g; only the mass of the fortune cookie was lower, i.e., 28 g owing to its low density. Figures 3 and 4 show the photographs of each sweet.

Table 3. Sweets chosen as candidate fuels.

Candidate sweets	Shape
Soft Candy Puccho (Japan)	Block candy
Snickers (U.S.A.)	Stick
HARIBO (Germany)	Small gummi
Madeleine (France)	Soft cookie
Fortune cookie (China)	Hard cookie

Fig. 3. Sweets as candidate hybrid rocket fuels.

Fig. 4. Soft candy Puccho in the chamber.

2.3. Firing test

All the firing tests were successful, and we could obtain the pressure and thrust profiles during combustion; however, we lost the Madeleine test data because of human error. Figure 5 and Table 4 show obtained data of the thrust curve and test results for each sweet. Snickers has the largest thrust of approximately 600 N, and its average thrust is also a large value of approximately 418.3 N. However, an extremely short burn time (1.76 s) is measured for it, which might be because of the meltable material (chocolate), which is the main component of Snickers. HARIBO exhibits a poor performance compared with other sweets. After the HARIBO test, we found some unburnt HARIBOs on the ground in the exhaust direction. This suggests that some of the small HARIBOs were ejected outside through the baffle plate and nozzle when it was ignited. The combustion oscillation is observed at a short burning time for the fortune cookie. A fortune cookie is very hard and brittle; therefore, it is theorized that the cookies are broken by the impact of the ignition and passed through the nozzle causing combustion oscillation. The firing test of the soft candy produces a very stable thrust curve and the highest total impulse (921.7 Ns) is recorded for it. The reason for the stable combustion is that the soft candy is harder and has better elasticity as a solid fuel, and it burns uniformly on the solid surface. Its average thrust level is 351.8 N, average oxidizer mass flux range is 300 kg/m²s, average pressure range 2.5 MPa, and burning time 2.62 s. Therefore, in this propulsion system, the Japanese soft candy was chosen as the hybrid rocket fuel. However, students can select other fuels on the basis of the rocket propulsion engineering design.

Fig. 5. Comparison of the combustion results of the sweets.

Table 4. Results of the firing tests.

Sweets	Ave. thrust / Burn Time	Isp	Result
Soft candy	351.8 N / 2.6 s	168.2 s	Highest total impulse
Snickers	418.3 N / 1.8 s	162.3 s	Highest thrust
HARIBO	239.0 N / 2.3 s	101.5 s	Did not burn completely
Madeleine	Not measured	Not measured	-
Fortune cookie	307.8 N / 2.0 s	108.2 s	Low density and bulky

3. Small Rocket Launch Experiment

We designed a small rocket based on these results and conducted a launch experiment in Japan. Four hybrid rockets equipped with the candy motor were launched successfully. Two of them were for the Candy Hybrid Rocket project, other two were for an educational program.

3.1. Candy hybrid rocket project

Here, we introduce the Candy Rocket Project under which the first launching experiment was conducted using the educational motor.

A launch experiment of a candy rocket was tested at the Kada Cosmo Park in Wakayama Prefecture on Saturday, March 7, 2015. The rocket was developed by SOUKI Systems Co. Ltd. The launching experiment was attempted twice and was successful. Specifications of the rocket are shown in Fig. 6 and Table 5.

Fig. 6. Schematic of the candy motor-loaded hybrid rocket.

Table 5. Specifications of the candy motor-loaded rocket.

Length	1800 mm
Diameter	150 mm
Dry weight	10 kg
Motor	Candy hybrid rocket
Recovery	Parachute
Cal. altitude	Approximately 313 m
Drop speed	Approximately 9 m/s
Down range	100 m around
Payload	Video camera Acceleration sensor Pressure sensor Sound beacon for recovery

The experiment was conducted twice using similarly shaped rockets. The loaded sensors were also successful in measuring the acceleration and atmospheric pressure. Figure 7 shows the analysis results of the measured pressure sensor data. According to it, the rocket practically attains the predicted altitude and drop speed. The motor carries the candy rocket to 319 m in altitude and is fully functional under the high-acceleration environment, as shown in Fig. 8.

Fig. 7. Analysis data from the pressure sensor.

Fig. 8. Successful launch of the candy rocket.

When launching the candy rocket, we invited approximately 20 children and assembled the candy rocket engine in front of them. Most of the children could not imagine that a rocket could be launched using soft candy as a fuel. We jubilated at the time of the rocket launch having satisfied the expectations of the children. The launch was a tremendous success for the field of space education.

In addition, this candy rocket was the first global challenge of its type, and was covered by various forms of the media. On the television, it was featured in 17 programs with detailed commentary. It was reported in 23 newspapers, and it is noteworthy that it was also published in sports newspapers that are not even remotely connected with space development. It was also highlighted on 550 news web sites.¹⁰⁾ Numerous English translations were also provided to the foreign media and reported in more than 30 countries worldwide. From these facts, we believe that sufficient results supporting space education have been provided indirectly through the media.

3.2. Educational program for rocket girls and boys¹¹⁾

The educational program for rocket girls and boys pertains to the design, construction, and launching of the small hybrid rocket by a group of high school students of approximately 20 members, and it is conducted every year. Several high school students join this program, and not only design and develop rockets, but also learn project management. In 2016, two rockets, labelled separately as team A and team B, were developed, and launched using the candy rocket motor for learning propulsion engineering. Figures 9 and 10 illustrate the schematic of the two rockets, and Tables 6 and 7 list their specifications.

Fig. 9. Schematic of the candy motor-loaded hybrid rocket of team A.

Table 6. Specifications of the rocket of team A.

Rocket name	MP3
Length [mm]	1310
Diameter [mm]	89
Wet weight [g]	4240
Dry weight [g]	3670
Cal. altitude [m]	1289
Motor	Candy rocket motor

Fig. 10. Schematic of the candy motor-loaded hybrid rocket of team B.

Table 7. Specifications of the rocket of team B.

Rocket name	Flying chicken
Length [mm]	1750
Diameter [mm]	89
Wet weight [g]	4652
Dry weight [g]	4322
Cal. altitude [m]	1187
Motor	Candy rocket motor

These rockets were launched at the Izu Oshima Island in the Tokyo metropolitan from March 25 to 27, 2017. The ignition of both the rockets was successful; however, the parachute of team A's rocket got detached because of the huge opening shock of the parachute, and the rocket had a hard landing. The recovery system of the rocket of team B did not work and it also had a hard free fall landing. Figures 11–13 show the photographs of these rocket launches and the recovered rocket of team B.

Fig. 11. Rocket launch of team A.

Fig. 12. Rocket launch of team B.

Fig. 13. Broken rocket from the hard landing of team B.

4. Conclusions

In this study, a reusable educational hybrid rocket motor was developed and was successfully launched four times. This motor could burn various materials as fuels. Therefore, high school students and undergraduate students can use it to learn rocket propulsion engineering. Members of the educational program for rocket girls and boys, who were high school students, used the educational motor to launch experiments and succeeded in their educational program.

Through this study, we want people to learn that creative thinking could turn an everyday material, such as candy, into something entirely different like rocket fuel. We want to communicate the importance of imagination, fascination of science, and the joy of creative manufacturing to people in every strata of society.

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