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Article

Fabrication of Potassium Nitrate-Sorbitol Propellant for Small Rocket System

Chanmin Chung

Korean Minjok Leadership Academy, Hoengseong-gun 25268, Korea; chanmin0404g@gmail.com

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Abstract: Potassium nitrate-sorbitol (KNSB) is a sugar-based solid rocket propellant widely used in amateur rocketry due to its stable combustion, ease of fabrication, and moderate burn rate. In this study, the design, fabrication, and performance evaluation of a small-scale KNSB-powered rocket were presented. The combustion test results were compared with theoretical calculations to assess deviations to refine the propellant formulation and rocket design. Computational simulations, experimental testing, and structural design optimization conducted in this study provide a reference for secondary school science and engineering courses. They also contribute to the advancement of KNSB rocketry applications in secondary education with information on how to optimize propellant characteristics and rocket system design with students.

Keywords: KSNB, Rocketry, Science, Engineering, Secondary education, Design, Fabrication, Performance evaluation

1. Introduction

Solid rocket propellants are regarded as a reliable and efficient means of propulsion for military, space exploration, and amateur rocketry. While liquid propellants for rocket engines require complicated fuel and oxidizer delivery systems, solid propellants enable simplicity, robustness, and ease of handling. Therefore, solid propellants are commonly used in launching missiles and amateur experimental rockets, especially at the booster stage due to their high energy density and rapid ignition properties [1].

Potassium nitrate-sorbitol (KNO_3- $C_6H_{14}O_6$, KNSB) is a sugar-based solid rocket propellant that has been widely used among amateur rocketry enthusiasts and experimental researchers. It consists of KNO_3 as the oxidizer and sorbitol as the fuel. KNSB has advantages including a high specific impulse (130–140 seconds at sea level), ease of manufacturing, and a lower combustion temperature compared with conventional composite propellants. Such advantages enable KNSB to reduce the risk of motor erosion and thermal damage [2], a moderate burn rate, and stable combustion, which makes KNSB a popular alternative to other sugar-based propellants such as potassium nitrate-sucrose (KNSU) [3]. KNSB exhibits a predictable thrust curve with minimal residue after combustion, thereby proving itself as a viable solid propellant for amateur rocketry [4].

Previous research on KNSB has been carried out to examine its combustion characteristics, burn rate, and performance with various engine parameters. It was found that the burn rate of KNSB relies on the grain geometry and chamber pressure of 2 to 5 mm/s in normal operating conditions [4]. KNSB's combustion efficiency is affected by the homogeneity of the fuel-oxidizer mixture and its casting process. KNSB's combustion properties and performance in controlled laboratory conditions have been explored extensively, involving advanced instrumentation and various testing environments. However, KNSB fabrication, thrust measurement, and flight performance evaluation still need to be further studied to enhance an understanding of KNSB's applications in education.

Therefore, we fabricated and analyzed small-scale KNSB rocketry for science and engineering education. The designed rocket using KNSB was tested to evaluate the burn rate and thrust by comparing it with the expected values that were calculated using the relevant software. The process of the rocket fabrication and the results of the combustion test provide a reference for various applications and designs of KSNB rocketry experiments in curricula.

2. Materials and Methods

Solid propellant rocketry comprises a rocket motor, a recovery system, and a launching system. In the rocket motor, a casing, nozzle, and propellent are included while the recovery system contains parachutes and the necessary circuitry and peripherals. In this study, we fabricated the essential components and assembled them to complete a KNSB rocket and tested the rocket to examine its flight capability and the components' performance.

2.1 Rocket Motor

2.1.1 KNSB Propellant

KNSB propellant is one of the most widely used solid propellants for amateur solid rockets. It is fabricated by mixing sorbitol and KNO_3. Sorbitol is usually added because it forms a soft lump after melting and cooling and is not hardened immediately after being mixed. When sorbitol reacts with KNO_3, it produces high heat and combusts instantly. Such properties with its easy accessibility, have made KNSB popular for rocket experiments. However, the heat and energy produced by the fuel depend on the mixing ratio of sorbitol and potassium nitrate. Therefore, it is necessary to examine the optimal mixing ratio of KNO_3 and sorbitol. To fabricate 100g of KNSB propellant, we determined an optimized mixing ratio of KNO_3, sorbitol, potassium perchlorate ($KClO_4$), and iron(III) oxide (Fe_2O_3). In KNSB, sorbitol is added as the igniter, while the rest act as oxidizers. To determine the optimal ratio for the required pressure and heat output of the fabrication in this study, we referred to Breaking Ballistics and Richard Nakka's Experimental Rocketry Website [3] and employed NASA's Chemical Equilibrium with Applications (CEA) for fuel property analysis [5]. The burn rate and output pressure were simulated using NASA's software (Fig. 1). Through iterative simulation, we determined the ingredient ratio of 32.4 (sorbitol): 32.4 (KNO_3) :27.8 ($KClO_4$) : 7.4 (Fe_2O_3). To fabricate KNSB, high-purity grade chemical ingredients were purchased from Duksan Pue Chemicals Co. Ltd. (KNO_3), Daejung Pharma Co. Ltd. ($KClO_4$), Samchun Chemicals Co. Ltd. (Fe_2O_3), and Samyang Chemical Co. Ltd (sorbitol).

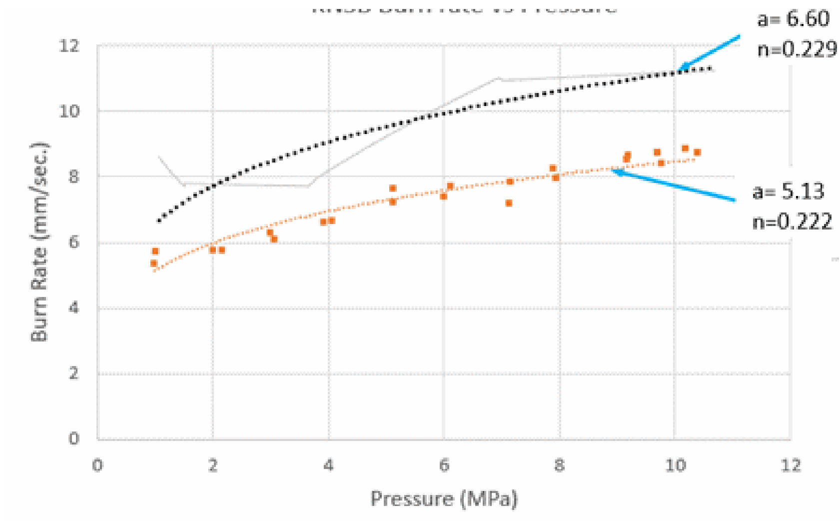


Fig. 1. Experimental results of KNSB's rate and output pressure.

In the fabrication of KNSB, the ingredients were heated and melted, then mixed, and solidified. To solidify KNSB and insert it into the rocket engine, a cylindrical mold needs to be fabricated. The mold was 3D-printed, and a release agent was used to prevent the solidified KNSB from sticking to the mold's walls and base. The release agent was sprayed on the inside of the mold. Then, KNSB was inserted into the mold and dried. KNSB was separated from the mold completely. Upon prolonged exposure to air, the solidified KNSB underwent recrystallization, transforming into a powder-like state. The melting point of KNSB was 95 to 100°C (Fig. 2).

Fig. 2. KNSB solidified with drilled hole in mold.

After fabricating KNSB, it was experimented with for combustion to examine its burning performance. To test the burning performance, we fabricated a simple and reliable igniter using a nichrome wire. To operate the igniter, we also made a remote controller containing a transmitter.

2.1.2 Nozzle

Various nozzles are used for rockets with their advantages and disadvantages: conical, bell-shaped (De Laval), annular, expansion-deflection, and plug nozzles. The nozzle is essential for rockets as it increases the speed of the output pressure from the ignited propellant injected from the engine. In this study, we adopted a conical as it is simple in design, cost-effective, easy to fabricate, and provides sufficient thrust for small-scale rockets and distributes thermal and mechanical stresses effectively to ensure durability during combustion and high-temperature operation [6]. In the design of the nozzle, atmospheric pressure plays an important role. As the altitude increases, the atmospheric pressure decreases, which reduces the maximum thrust, specific impulse, and thrust coefficient. Therefore, the nozzle must be designed considering such variations.

The expansion ratio of the nozzle was estimated considering the nozzle exit area, atmospheric pressure, thrust coefficient, combustion chamber pressure, and fuel characteristics. Equation (1) was used to calculate the expansion ratio.

$$\epsilon = \frac{A_e}{A_t} = \frac{1}{\left(\frac{\gamma+1}{2}\right)^{\frac{1}{\gamma-1}}\left(\frac{P_e}{P_c}\right)^{\frac{1}{\gamma}}\sqrt{\frac{\gamma+1}{\gamma-1}\left[1-\left(\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}} \quad (1)$$

where A_e is the exit area of the nozzle, A_t is the throat area of the nozzle, γ is the specific heat ratio, P_e is the exit pressure of the nozzle, P_c is the pressure of the combustion chamber.

Figure 3 shows the dimensions and a simple diagram of the designed nozzle in this study.

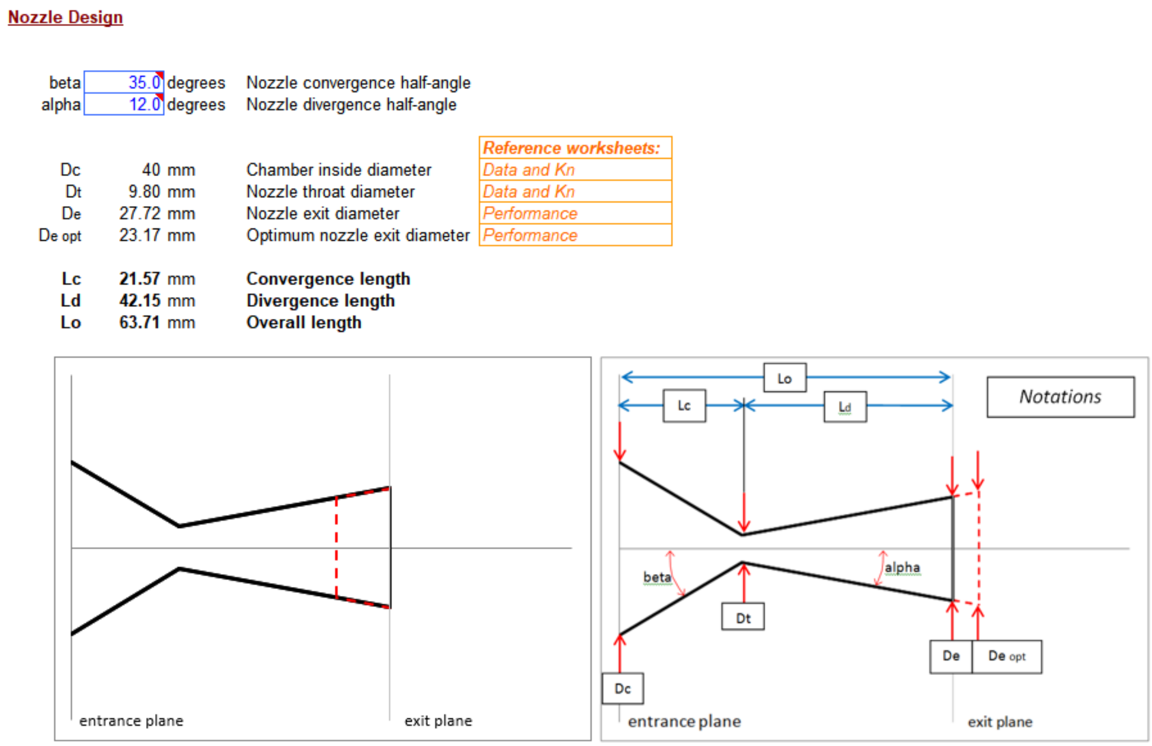


Fig. 3. Designed nozzle and its dimensions of KNSB rocket fabricated in this study.

With the fabricated propellant and conical nozzle, we designed the body of rockets with fins as shown in Figure 4.

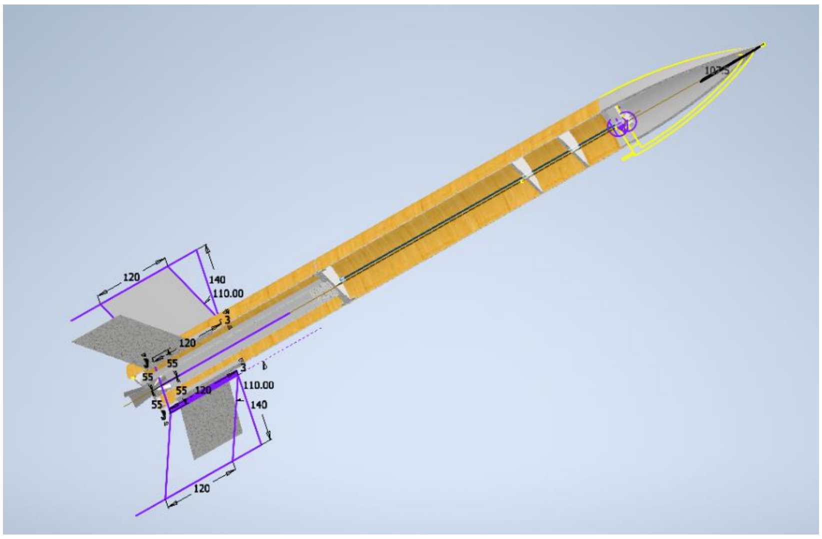


Fig. 4. Structure of designed rocket in this study.

2.2 Recovery System

A parachute ejection system was designed in the recovery system of the fabricated KSNB rocket. The system consisted of a nose cone, a parachute, and an ejection module. To recover the rocket safely on the ground, the parachute must be deployed at an appropriate height. To accurately control the parachute ejection, a computer with three components was installed on the rocket: an altimeter, an Arduino circuitry, and a battery.

2.2.1 Nose cone

The nose cone of the parachute ejection system needs an aerodynamic design. We designed it as an ellipse with an appropriate fineness ratio. The fineness ratio is the height of the nose cone divided by the diameter of the base of the nose cone. The larger the fineness ratio, the smaller the drag coefficient indicating that the rocket experiences less drag. After the diameter of the base was determined in the rocket body design, the size of the nose cone was calculated. In this study, the fineness ratio of the nose cone was set to 2.25. Since the diameter of the rocket body was 100 mm, the height of the nose cone was 270 mm. Using Fusion 360, a 3D CAD program, the exact design of the nose cone was created (Table 1).

Table 1. Dimensions of nose cone of parachute ejection system in this study.

Dimension	Value
Height	270 mm
Thickness	3 mm
Base diameter	104 mm
Base thickness	3 mm
Raw material	Polylactic acid

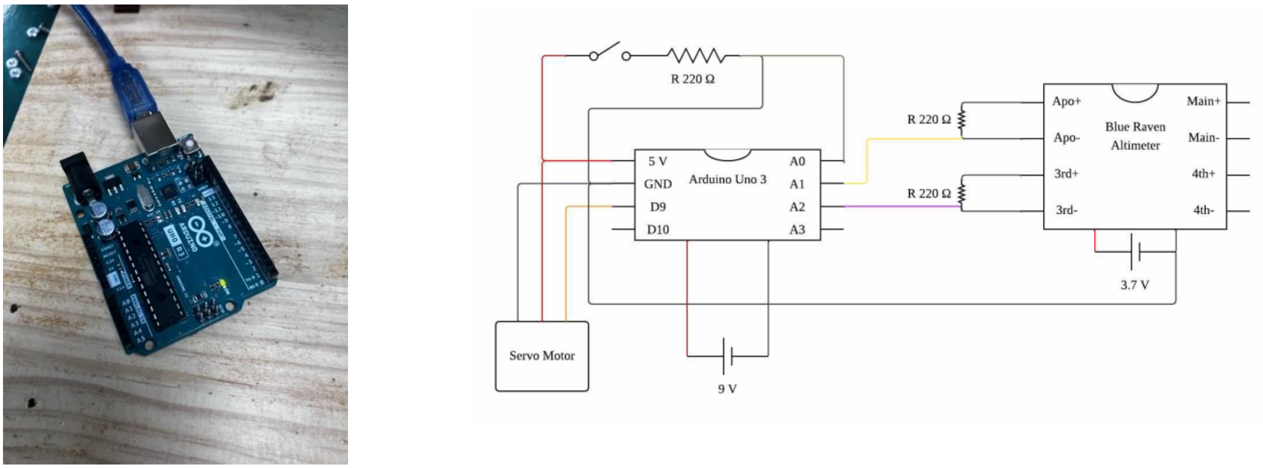
While black powder is widely used for parachute ejection, we employed servo motors and a spring to eject the parachute. A Blue Raven Altimeter (Fig. 5) was used through the Featherweight UI app. The altimeter was contained in the Bay Kit 38 mm (Apogee Components LLC, the United States) and installed on the rocket. The altimeter transmitted electric signals to operate the servo motor through a circuit designed in this study using Arduino.

(a) (b) (c)

Fig. 5. **(a)** Dimension of blue raven 4 altimeter; **(b)** Images of blue raven 4 altimeter; **(c)** Avionics bay kit.

2.2 Ejection module

The Arduino circuit activated the parachute ejection module by the transmitted data from the altimeter. The Arduino Uno 3 board was selected for the rocket as it is versatile and can be programmed using the Arduino ID easily. Figure 6 shows the circuitry of the ejection module.



(a) Ejection module **(b)** Circuit of ejection module

Fig. 6. Arduino Uno 3 used in parachute ejection module.

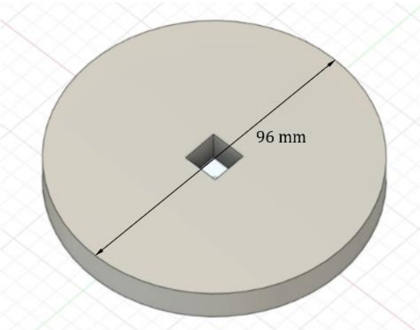
The Arduino code was established as follows.

```
#include <Servo.h>
Servo releaseMotor;

int servoPin = 9;
int potPin = A0;
int altPin = A1;
int altBackupPin = A2;
bool deployed = false;

const int TARGET_ANGLE = 50;

void setup() {
  releaseMotor.attach(servoPin);
  releaseMotor.write(90);
```

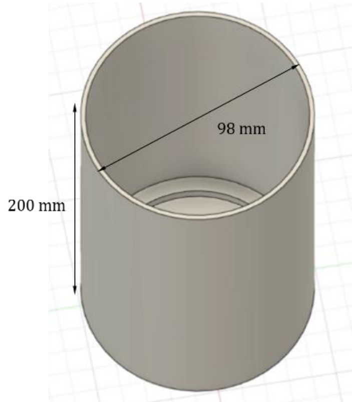
```
    delay(1000);
    deployed = false;
  }


  void loop() {
    if(deployed == false)
    {
      int altReading = analogRead(altPin);
      int altBackupReading = analogRead(altBackupPin);
      if(altReading > 10)
        //Main Deploy
        releaseMotor.write(TARGET_ANGLE);
        delay(2000);
        if(releaseMotor.read() > TARGET_ANGLE / 2) deployed = true;          }
      if(altBackupReading > 10)             //Backup Deploy
        releaseMotor.write(TARGET_ANGLE);
        delay(2000);
        if(releaseMotor.read() > TARGET_ANGLE / 2) deployed = true;          }
      else
      {
        int potReading, potMapped;
        potReading = analogRead(potPin);
        potMapped = map(potReading, 0, 1023, 0, 50) + 5;
        releaseMotor.write(potMapped);
      }
    }
  }
```

2.3 Components of system

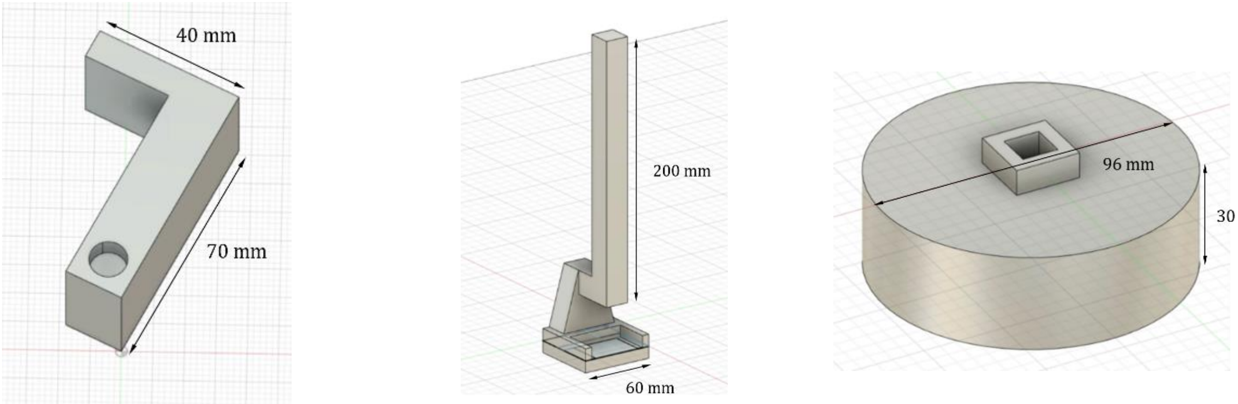
The components of the parachute ejection system were designed, 3D printed, and then assembled. Two hooks were added to hold two servo motors to rotate at the same angle (Fig. 7). The fabricated components were assembled with the Arduino circuit, and the ejection module in the nose cone.



(a)



(b)



(c) (d) (e)

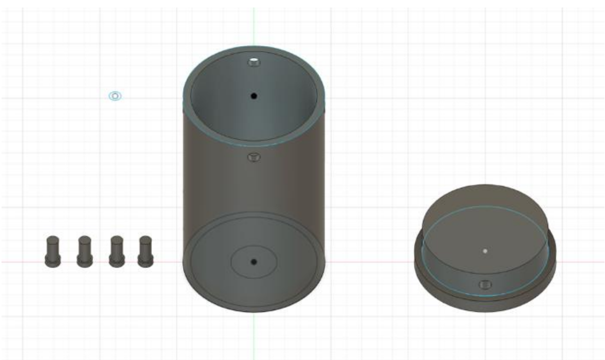
Fig. 7. Components of parachute ejection system in this study: **(a)** Parachute pushing plate; **(b)** Container of ejection module; **(c)** First hook to hold servo motors; **(d)** Sencod hook to pull spring connected to the fist hook; **(e)** Spring supporter.

2.3 Launching System

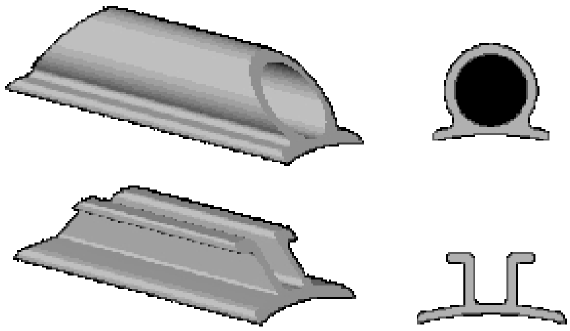
A rocket launch pad was designed to launch a rocket without a ground run and enable directional control in launching a small rocket. In the initial stage of flight, a small rocket cannot control its attitude due to insufficient thrust as the thrust vector control (TVC) technology cannot be adopted. Therefore, the launch pad plays a pivotal role in the attitude control of a small rocket. Without it, the rocket might fly in an unpredictable direction with an unstable burn or hard start (Fig. 8).

Fig. 8. Dimensions of assembled launch pad in this study.

The launch pad was assembled with aluminum profiles using bolts, nuts, and brackets. To distribute the weight and support the load from the rocket, the launch angle was designed to be perpendicular to the ground stably. Two launch rails were arranged in parallel to increase stability, and the launch angle was adjusted by rotating the pivot joint. To launch the rocket along a designed path, rail buttons were designed and 3D printed in this study while commercially available rail lugs were adopted (Fig. 9).



(a)

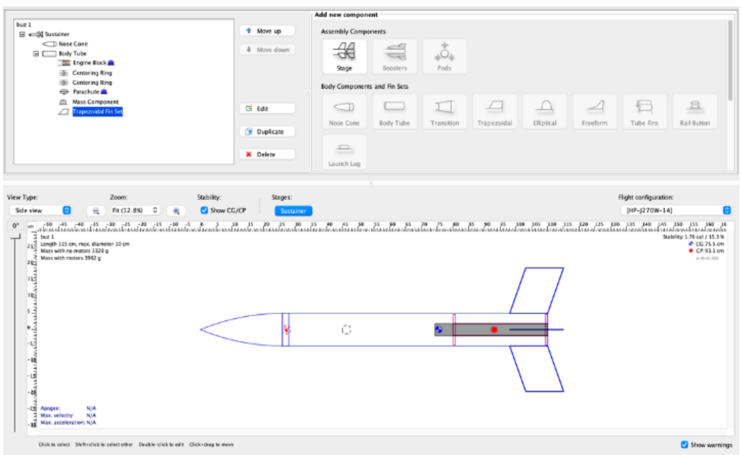


(b)

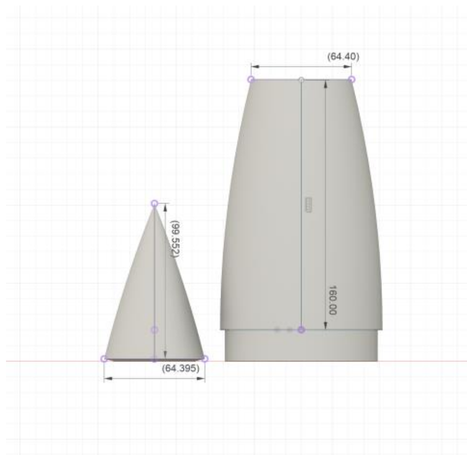
Fig. 9. (a) Designed rail buttons; **(b)** Purchased rail lugs.

2.4 Fin, Nosecone, and Casing

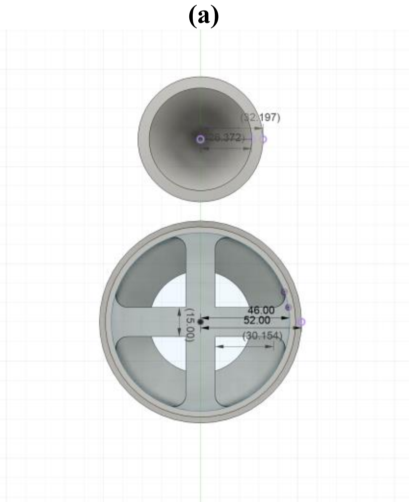
The body of the rocket was made of aluminum plates and carbon pillars to evenly distribute the force of the rocket engine. The nose cone and fins were designed, 3d-printed, and then, fixed to the rocket body. To ensure the stability of the rocket body, the rocket motor was designed using the OpenRocket Simulator to withstand the weight of the propellant (100 g). The front of the motor was made of a 10-mm aluminum sheet in a triangular structure to receive and transmit the thrust (Fig. 10).



(a)

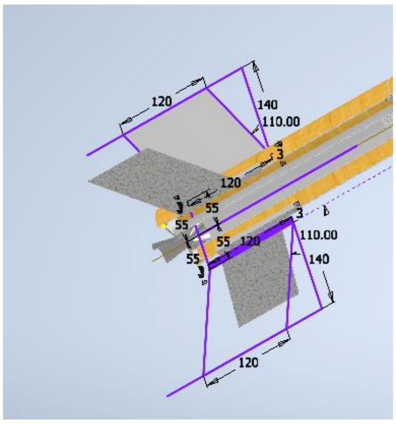


(b)



(c)

(d)



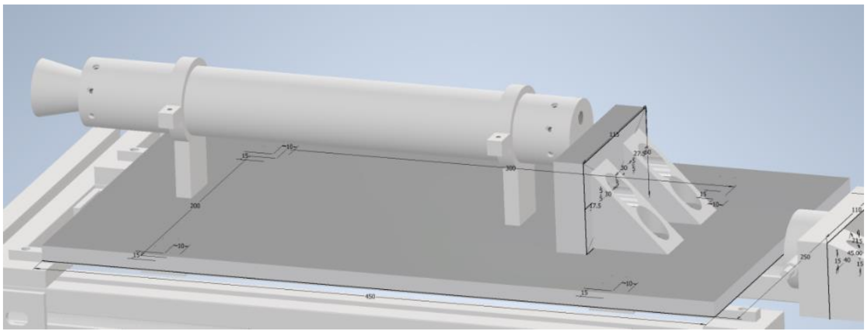
(e)

Fig. 10. (**a**) Design of rocket body; (**b, c**) 3D-printed nose cone; (**d**) Rocket engine; (**e**) Design of fins (in mm).

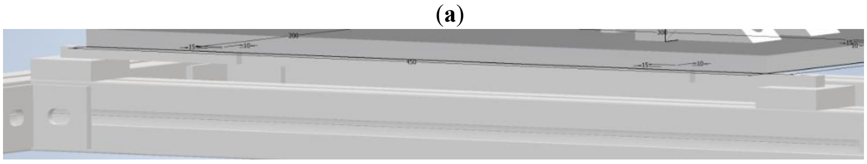
3. Results and Discussion

3.1 Test Mount

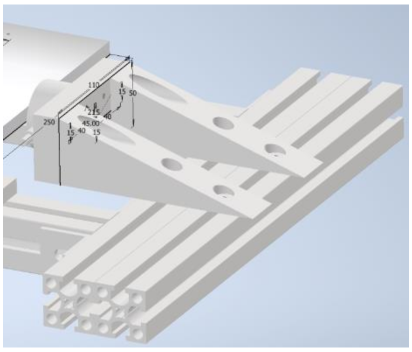
For the combustion experiment, a rocket test mount was designed as shown in Fig. 11. The test mount was built using the bogie method. The bogie method adopted a load cell to measure the force of the rocket motor pushing forward. The front part of the motor was made of a 10-mm aluminum sheet and a 5-mm aluminum plate. The aluminum sheet was used to surround the motor with a pressure sensor. The supporting pedestals were installed to stabilize the rocket motor and prevent it from lifting under forces applied along different axes. A linear rail (Korea Misumi Co. Ltd) was added to the test mount. The linear rail ensures smooth and precise linear motion in testing the rocket ending. It enables the accurate measurement of thrust forces applied to the rocket engine directed perpendicularly to the load cell by minimizing energy loss and errors. The load cell is used to measure the thrust generated by the rocket engine. It converts the mechanical force into an electrical signal to determine thrust. The linear rail used in this study was No. 9 rail with a maximum load of 1.86 kN (Table 2). The rail was fixed with 16 M3 screws to the test mount.



(**a**)



(**b**)



(**c**)

Fig. 11. (**a**) Design of test mount; (**b**) linear rail; (**c**) load cell.

Table 2. Speciation of linear rails attached to test mount of rocket engine in this study.

Model number	Dynamic load (kN)	Static load (kN)	Permissible momentum		Block weight (kg)	Guide weight (kg/m)
			Mx × My (N·m)	Mz (N·m)		
7	0.98	1.24	2.84	4.7	0.01	0.22
9	1.86	2.55	7.35	11.76	0.016	0.38
12	2.84	3.92	13.72	25.48	0.034	0.65
15	4.61	5.59	21.56	45.08	0.059	1

(Mx, My, and Mz: momentum on the *x*, *y*, and *z*-axis.)

3.2 Combustion Test

In the combustion test, the combustion duration was 2–3 seconds, which presented the characteristic of KNSB. The measured thrust by the time of the rocket engine is presented in Fig. 12. The thrust was calculated by using SRM 2023 of Richard Nakka's Experimental Rocketry Website (https://www.nakka-rocketry.net/softw.html#Meteor). The test and estimated values were compared as presented in Table 3. The rocket engine's measured performance demonstrated around 67% of the expected performance, while the burn time significantly exceeded the expected value, suggesting prolonged combustion. The measured average thrust was 40.3% of the expected value. The test values were smaller than the expected value, which suggested that the fuel characteristics caused larger errors than being supposed to. The burn time was longer than the expected time due to the cylindrical shape of the KNSB propellant used in this study, as it is not error-prone. The burn time depends on the fuel characteristics and grain shape, and since cylindrical grains are the simplest and least error-prone for grain shape, the error became small. While the ratio of KNO_3 to sorbitol and the purity of the propellant had a significant impact on the test error, it is necessary to optimize the ratio and purity to increase the thrust of KNSB.

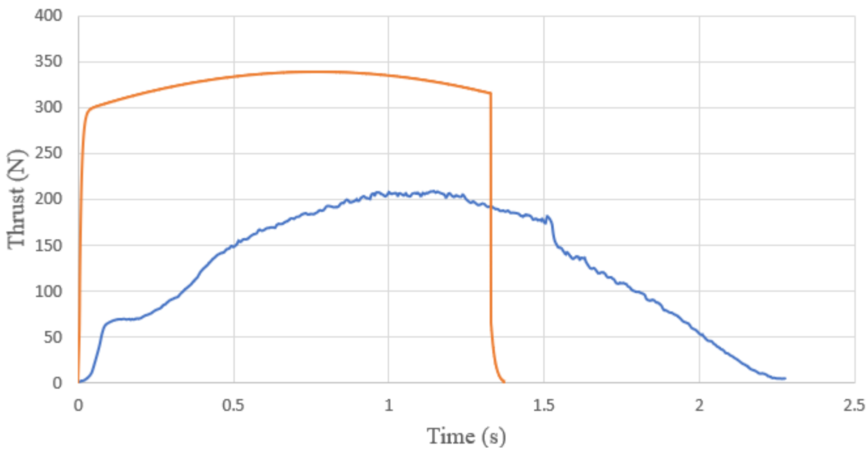


Fig. 12. Thrust over time or rocket engine in combustion test in this study (blue line: measured value, orange line: expected value).

Table 3. Measured and expected values of thrust in first combustion test of rocket ending in this study.

Parameter	Measured value	Expected value	Ratio (%)
Total thrust	293.67	435.0	67.5
Specific impulse	80.94	120.1	67.4
Burn time	2.27	1.37	166.6
Average thrust	128.26	318.0	40.3
Maximum thrust	209.56	338.6	61.9

4. Conclusion

In this study, the fabrication and testing of a small-scale KNSB rocket were demonstrated, highlighting the feasibility of educational and experimental applications. The experimental thrust and burn time results showed deviations from theoretical calculations, emphasizing the impact of grain geometry, propellant composition, and combustion conditions on performance. Despite the observed deviations, the rocket functioned effectively, and the implemented engine and parachute ejection system operated satisfactorily, presenting its performance and safe recovery. The importance of refining fuel formulations, optimizing combustion chamber conditions, and improving nozzle efficiency to enhance propulsion performance was verified, which can be experimented with in science and engineering courses for secondary education. The design, fabrication, and testing methods in this study can be referred to as a basis and reference in related classes, while they need to be modified or improved in further research by testing advanced propellant formulations, alternative nozzle designs, and high-precision thrust measurement with students.

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Data Availability Statement: The data of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest

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