Experimental investigation of solid rocket motors for small sounding rockets

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Abstract Experimentation and research of solid rocket motors are important subjects for aerospace engineering students. However, many institutes in Thailand rarely include experiments on solid rocket motors in research projects of aerospace engineering students, mainly because of the complexity of mixing the explosive propellants. This paper focuses on the design and construction of a solid rocket motor for total impulse in the class IJ that can be utilised as a small sounding rocket by researchers in the near future. Initially, the test stands intended for measuring the pressure in the combustion chamber and the thrust of the solid rocket motor were designed and constructed. The basic design of the propellant configuration was evaluated. Several formulas and ratios of solid propellants were compared for achieving the maximum thrust. The convenience of manufacturing and casting of the fabricated solid rocket motors were a critical consideration. The motor structural analysis such as the combustion chamber wall thickness was also discussed. Several types of nozzles were compared and evaluated for ensuring the maximum thrust of the solid rocket motors during the experiments. The theory of heat transfer analysis in the combustion chamber was discussed and compared with the experimental data.

1. Introduction
Solid rocket motor is a rocket engine that uses the combustion process to break the chemical energy bond of the fuel and oxidiser to produce the thrust for the rocket. The fuel and oxidiser are mixed together to form a well-combined mixture whereas the binder binds the fuel and oxidiser. Many types of fuel and oxidisers can be used in a solid rocket motor [1]. As the solid rocket motor contains this explosive material, there might be some concerns regarding the safety regulations and laws depending on the geographic location, which require several documents to be presented for purchase, handling, and storage of such materials [2]. However, the study of solid rocket motor has become a fundamental subject in the field of rocket propulsion for aerospace engineering students. For that reason, many aerospace engineering institutes around the world are interested in the theoretical and experimental study of sounding rockets, as they help students to directly experience, develop, and apply their knowledge of rocket propulsion.
In 2006, T. John et al demonstrated a launch vehicle for a small satellite using a sounding rocket [3]. In mid-2013, S. Singh designed and constructed a solid rocket motor that researchers could use as the main propulsion of a sounding rocket [4]. A Okinski et al developed the Polish small sounding rocket as a reusable CanSat launcher in 2015 [5]. In addition, sounding rockets for picosatellite launchers and rocket competitions have been studied and reported [6, 7].

This paper focuses on the development of the I-J class of solid rocket motors that use commercially available materials and chemicals for fuel and oxidiser as an alternative to avoid high cost, complex machining, and procurement challenges. It is a preliminary step for further development of solid rocket motors for Thai research students, which can enable them to design and construct rockets that have an altitude of 1.5 km in the near future.

2. Rocket Motor Principle

A basic rocket motor comprises three main parts: head cap, combustion chamber, and nozzle. The principal of rocket motor operation is shown in figure 1. Initially, the ignition fuse is ignited causing the propellant inside the combustion chamber to burn at a rapid rate. This combustion produces hot gas, which increases the pressure in the combustion chamber. The hot gas flows through the exit at the nozzle. Usually, the nozzle contains converging and diverging parts. The converging part has an exit area smaller than the entrance, which increases the velocity of the exhaust gas. The connecting part between the converging and diverging parts is called the throat. At this point, the velocity of the hot gas reaches the speed of sound, Mach (M) = 1. Beyond the throat, the exit area increases further to bring the hot gases to supersonic speed, as explained in the ‘de Laval nozzle’ [1, 2]. However, the pressure decreases as the gas flows through the nozzle.

![de Laval nozzle](image)

**Figure 1.** Principal of rocket motor operation.

The thrust is generated because of the increase in velocity of the hot gas and the pressure difference between the ambient and exit pressure at the nozzle. Thrust is given by the equation

\[ F = \dot{m}V_e + (P_e - P_a)A_e, \]

where \( F \) is the thrust (N), \( \dot{m} \) is the mass flow rate (kg/s), \( V_e \) is the exit velocity of the hot gas (m/s), \( P_e, P_a \) are the exit pressure at the nozzle and the ambient pressure respectively, and \( A_e \) is the exit area of the nozzle.

2.1. Rocket propellant

Rocket propellant is a well-combined mixture of fuel and oxidiser. The oxidiser provides oxygen for the fuel to burn. In some cases, a binder can be used for increasing the flexibility of the mixture in the casting process. The ratio of the fuel and oxidiser can be altered or the combustion chamber parameters can be changed to get different burn rates. The fuel and oxidiser are commercial grade and available with local suppliers. In this study, the appropriate ratio of fuel and oxidiser were obtained as follows.
2.1.1. **Black powder.** Traditionally, the black powder is prepared by dry mixing 15% charcoal powder, 10% sulphur powder, and 75% potassium nitrate by weight, and 1 g dextrin is added per 100 g of the mixture. The ingredients were mixed together for nearly 2 min in a plastic container to prevent electrostatic discharge. The black powder can be used as a fuse ignitor, as it burns rapidly. The maximum combustion temperature is approximately 1400 °C [8].

2.1.2. **White mixed powder.** In this study, white powder consisted of 65% potassium nitrate and 35% sugar powder by weight mixed well together. The final mixed white powder can absorb the moisture in the air; so, it must be kept sealed in an airtight container if meant for later use. The combustion temperature of the white mixed powder was approximately 1200–1300 °C.

2.1.3. **Rocket Candy or R-Candy.** This propellant used in our study contained a combination of sugar syrup, potassium nitrate, and sugar powder in the ratio of 65%, 18%, and 17% by weight, respectively. In this research, the rocket candy was prepared using an electric pot, as can be seen in figure 2. Initially, the sugar syrup was heated to boiling temperature. Then, sugar powder and potassium nitrate were mixed in it and the syrup was heated until it started boiling again, after which the electric pot was turned off and the hot mixture was poured into the moulds. The combustion temperature of R-Candy was approximately 1347 °C [9].

2.2. **Material and propellant selection**

The propellant selection criteria for cost and safe handling are commercially available. Based on the criteria, the white mixed powder was selected as the first propellant to test in rocket motor class I and the second propellant was prepared with the R-Candy for rocket motor class J. The segments used were PVC 5 and PVC 13.5 pipes, which contained the white mixed powder and R-Candy, respectively. The end burning with white mixed powder and tubular grain configurations with R-Candy were prepared. The end burning was quite easy to prepare in the PVC pipe; however, the tubular grain configuration was quite difficult to prepare in the casting and moulding process, as there was a risk of the R-Candy solidifying if the process took longer than 10 min. The wooden base was 1-in thick, and the rod used to cast and mould was ¾-in in diameter; the moulds and the PVC can be seen in figure 3.

![Figure 2. Rocket Candy heating in the PVC propellant electric pot.](image1.png)

![Figure 3. Casting and moulding the propellants into segments.](image2.png)
3. Rocket Motor Design
The rocket motor consists of head cap, combustion chamber, nozzle, igniter charge, and propellant grain segment, as can be seen in figure 4.

![Figure 4. Basic rocket motor components.](image)

3.1. Propellant grain segment using white powder
Four types of rocket motor nozzles were used in this study. The first was a straight connector of length ¼ in between the internal thread and outer thread. The second was the reduction connector from ¼ to ½ in, which acted as a divergent nozzle. Next was a straight internal thread connector with a washer as a throat inside the connector. Last was a straight internal thread connector without a washer. The completely assembled rocket motors are shown in figure 5. The length of the ¼-in PVC 5 tube was 5 in and it was filled with white mixed powder propellant with total propellant weights of 82.8, 85.5, 76.0, and 77.1 g, respectively. Then, the ¼-in head cap was connected to the PVC 5 tube and nozzle. The fuse ignitor was connected with the electrical wire and taped to the nozzle to avoid falling off.

![Figure 5. Rocket motors assembled with white powder propellant.](image)

3.2. Propellant grain segment using Rocket Candy
For this study, R.Candy with tubular grain segment was selected with PVC 13.5 as the propellant grain segment. The molten R-Candy was cast into the prepared segments. The total lengths of the propellant grain segments were 2.5 in, 5 in, 10 in, and 15 in. The propellant grain segments of length 2.5 in were selected, as the propellant could be conveniently cast and moulded into this length. Then, each 2.5 in segment was connected with electrical tape together until the required lengths of 5 in, 10 in, and 15 in were obtained. Next, the grain segments were slid into the PVC 13.5 shells of 3-in diameters. The fuse
ignitor was placed at the top of the propellant segment so that it could burn rapidly and then, the head cap, outer shell, and nozzle were assembled together. The rocket numbers one to five were prepared with 2.5 in, 5 in, 10 in, and two 15 in propeller segments, respectively, as shown in figure 6.

3.3. Nozzle
Nozzle is the part that produces thrust in a rocket motor; the exhaust gases rapidly flow with increasing velocity as they pass through the throat and exit to the atmosphere. In the case of R-Candy propellant, the nozzle was cast with concrete and the washer was placed at the throat to sustain the high temperature and pressure, as can be seen in figure 7. The mixing ratio of concrete and water was 1:0.35 by weight [10]. The ratios of the divergent part of the nozzle can be seen in figure 8. The throat diameter was 1.5 cm and the exit nozzle diameter was 9.8 cm. For simplicity, the converging part of the nozzle was not included in the measurements.

![Figure 7: Nozzles manufactured using concrete and 2-in PVC connectors.](image)

![Figure 8: Dimensions of the rocket nozzle.](image)

3.4. Ignition fuse and ignition system
Electrical ignitor switches are required for safety purposes. There are two types of switches—pre-fire and fire switches—as can be seen in figure 9. The wire from the switch was connected to the rocket motor and the other side of the switch was connected to the battery of 12 V and 8 Ah.

![Figure 9: Electrical ignition switches.](image)
3.5. Heat transfer analysis in combustion chamber

In this study, only conduction and convection were considered inside the combustion chamber and the radiation was neglected for simplicity. The 1D heat conduction is the transfer of heat through a material (solid, liquid, or gas) and can be expressed as:

\[ q'' = -k \frac{dT}{dx} = \frac{k}{L} (T_{WH} - T_{WC}), \]

where \( q'' \) is the heat flux, \( k \) is the thermal conductivity of the material, \( L \) is the thickness of the material, and \( T_{WH} \) and \( T_{WC} \) are the hot wall and cold wall temperatures. The 1D heat convection is the transfer of heat from a surface (liquid or solid) to a fluid in motion and is described by:

\[ q'' = h(T_G - T_W), \]

where \( h \) is the convection coefficient, and \( T_G \) and \( T_W \) are combustion gas temperature and wall temperature, respectively. The heat flows during conduction and convection are shown in figure 10 and figure 11, respectively. For safety reasons, the combustion chamber temperature was assumed to be approximately 2000–2500 °C.

![Figure 10. 1D heat conduction.](image)

![Figure 11. 1D heat convection.](image)

3.6. Static rocket motor test stand

The static rocket motor test stands were made with square steel and connected together with screw. The width, length, and height of the stand were measured as shown in figure 12, and were 50 cm, 50 cm, and 150 cm, respectively. This test stand could be transported via a sedan. Moreover, the test stand could be used in the vertical or horizontal position. The total weight of the stand was around 30 kg. The rocket motor was tightly secured into this test stand. The thrust force of the rocket motor was recorded using a digital scale and a camera recorder, as can be seen in figure 13.
3.7. Safety regulations
Safety was our first priority in this lab and we followed the safety regulations for an amateur rocket [11]. In addition, a screen was used to cover the structure to prevent the debris from scattering except on one side, which was kept open to release the exhaust gases. The surrounding area was cleared and prepared for the test every time.

4. Testing and Results
The rocket motor numbers one to four, which used white mixed powder, provided the total impulse of approximately 100 N·s, which is similar to that of a class G rocket. The end burning time was determined as approximately 30 s using the camera recorder. The initial propellant weight was approximately 78–82 g and the average thrust was around 3.2–3.6 N. The total impulse was calculated as approximately 98–110 N·s and the maximum thrust was measured by a digital weight as approximately 83–103 N. However, the maximum thrust of the rocket motor number one could not be measured, as the combustion chamber melted and developed a hole of approximately 2-mm diameter because its burning time was longer than that of the other parts. Based on the results, the rocket motor number two provided the maximum thrust using the divergent nozzle. The heat flux was approximately 0.35–0.44 MW, assuming that the thermal conductivity of PVC is 0.19 W/(m K) and its melting point is approximately 160 °C [12-13]. The results for the white mixed powder rocket motor can be seen in Table 1, assuming that the specific impulse (I_sp) of the white mixed powder and R-Candy [1-2] is approximately 130 s. The total impulse (I) can be calculated as:

\[ I = (W_p) (I_{sp}) \]  \hspace{1cm} (4)

where I is the total impulse, W_p is the propellant weight, and I_sp is the specific impulse.

| Rocket number | Burning time (s) | Propellant weight (g) | Average thrust (N) | Total impulse (N·s) | Maximum thrust (N) |
|---------------|------------------|-----------------------|--------------------|---------------------|-------------------|
| 1             | 32               | 82.8                  | 3.29               | 105.59              | -                 |
| 2             | 30               | 85.5                  | 3.63               | 109.04              | 103.63            |
| 3             | 27               | 76.5                  | 3.61               | 97.56               | 93.61             |
| 4             | 28               | 77.5                  | 3.53               | 98.70               | 83.53             |

Table 1. Testing results for the white mixed powder rocket motors.
The R-Candy rocket motor numbers one to four were categorised as rocket classes G, H, and I because the total impulse ranged within 80–160, 160–320, and 320–640 N·s [14]. The sensitivity of the digital scale was not very accurate because the maximum thrust varied during the test, as shown in table 2. However, the rocket numbers 4 and 5 misfired and exploded. There are several reasons for this, which include the casting process of R-Candy, alignment of the propellant segments, and expansion area ratio of the nozzle. The test stand was placed in the horizontal position, as can be seen in figure 14. It can be observed in tables 1 and 2 that the mass of the propellant increases with the total impulse, as shown in equation (3). The pressure gauge scale was connected but the scale had a wide range from 0–10000 psi because of which it could not detect and record the data for white mixed powder and R-Candy. The digital thrust via data acquisition was developed to record the thrust and pressure simultaneously; however, there were problems in the signal from the data acquisition to the computer, which resulted in unclear data.

Table 2. Testing results for R-Candy rocket motors.

| Rocket number | Burning time (s) | Propellant weight (g) | Average thrust (N) | Total impulse (N·s) | Maximum thrust (N) |
|---------------|------------------|-----------------------|--------------------|---------------------|--------------------|
| 1             | 17               | 107.1                 | 8.03               | 136.58              | >18.03             |
| 2             | 30               | 223.2                 | 9.49               | 284.65              | >39.49             |
| 3             | 10               | 452.7                 | 57.73              | 577.33              | >50.00             |

![Figure 14. Static rocket test stand firing in the horizontal position.](image)

5. Conclusions and Recommendations
It was observed in this research that the white mixed powder could be used for small class G rockets; the walls in the combustion chamber made of PVC 5 might not be able to sustain such high temperature and long combustion duration of more than approximately 32 s for this class of rockets. The divergent nozzle is the most suitable, as it provides the maximum thrust. For rockets of higher class, the walls need to be thicker, such as of PVC 13.5, to prevent melting. However, an outer pipe should be used to cover the propellant segment in the interest of safety. The classification of R-Candy propellant rocket motors from classes G to I was successfully performed and recorded; however, the class J rocket motors misfired and exploded.

In conclusion, the rocket motors were successfully tested and classified, and this study of the rocket motor can be used for determining the flight of rockets in the near future.

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