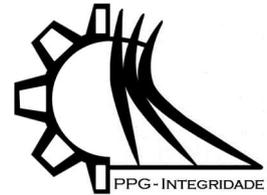




ISSN 2447-6102



Article

# COMPARATIVE ANALYSIS OF THE PERFORMANCE OF SOLID PROPELLANTS PRODUCED BY COLD PRESSING AND THERMAL MELTING IN MINIROCKETS

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Received: Outubro/2025; Accepted: Novembro/2025; Published: Novembro/2025

**Abstract:** The application of small-scale aerospace technologies in academic settings, particularly minirockets, represents a strategic area of research, as it allows for experimental validation in a controlled environment and at a low operational cost. In particular, the use of solid propellants has become prominent within experimental rocketry, especially formulations based on potassium nitrate (KNO<sub>3</sub>), whose ease of preparation and energy efficiency make them ideal for educational and experimental purposes. Accordingly, this work presents a quantitative experimental study aimed at the comparative analysis of two solid propellant manufacturing methods widely used in academic contexts: cold pressing and thermal melting (melt-casting). A single formulation composed mainly of potassium nitrate and sucrose was used as the basis to produce propellant grains via both processes. Their performance was then evaluated through static tests on a custom-built test stand equipped with force sensors, a data acquisition system, and capabilities for total impulse calculation. This production was a collaborative effort among university teams from Northeast Brazil. The results indicated significant differences in average thrust, combustion stability, ease of production, and associated risks, providing relevant technical insights for educational and research applications involving small-scale experimental rockets. Therefore, a clear trade-off between performance and reliability was observed, with the cold-pressing method being more variable in performance and susceptible to structural failures, while the thermal melting method proved to be more consistent in its power output.

**Keywords:** low-cost, academic rockets, KNSU, education.

## 1. Introduction

The development of technologies for the propulsion of small-scale aerospace vehicles, notably minirockets, constitutes a strategic research front for the consolidation of applied knowledge in aerospace engineering. Such systems serve as effective experimental platforms, especially in academic settings, as they allow for the empirical validation of theoretical concepts in controlled and low-cost operational contexts. Within this scope, the use of solid propellants has gained prominence in the field of scientific model rocketry, particularly formulations based on potassium nitrate (KNO<sub>3</sub>) and sucrose (C<sub>12</sub>H<sub>22</sub>O<sub>11</sub>), whose simplicity of preparation and energy efficiency make them ideal for educational and experimental purposes (Brinley, 1960).



Regarding the manufacturing of these propellants, two main approaches predominate: manufacturing by melting, also known as casting, and manufacturing by cold pressing. The melting method consists of the thermal fusion of previously micronized components at controlled temperatures between 120°C and 140°C. Cold pressing, in turn, is based on the mechanical compaction with a hydraulic press of the same reagents at room temperature as reported by Foltran, Moro and Silva et al. (2015). Studies such as those by Nakka (2023) suggest that melt-cast propellants exhibit better reproducibility and ballistic performance, whereas cold pressing, despite being safer than all other grain manufacturing methods (Marchi et al., 2021) and more accessible, may compromise the stability and repeatability of the burn.

## 2. Materials and Methods

This study is characterized as basic and exploratory experimental research. The primary objective is to conduct a comparative analysis of the ballistic performance of solid propellants produced by two distinct methods: thermal melting (hot-melt) and cold mechanical pressing under standardized static test conditions. The investigation employs a quantitative approach, utilizing measurable variables such as average thrust, burn time, and total impulse, alongside operational parameters related to the stability, storability, and safety of the propellant compounds. The exploratory nature of this research addresses a gap in literature concerning direct comparisons of these specific amateur manufacturing techniques. It is important to note that, due to the limited scope of the tests, the obtained results aim to establish a foundational understanding and indicate performance trends, rather than to validate the propellants for large-scale application without further, more extensive investigation.

The methodology involves the strict standardization of experimental hardware, including the motor casing, nozzle, and core geometry, to ensure fairness across tests and enable a statistically robust comparison between the manufacturing methods. This collaborative effort was carried out by the university rocketry teams of the Northeast Aerospace Federation (FAERNE): Sirius Rockets, the Cangaço no Espaço, Potiguar Rocket Designers (PRD), Cactus Rockets Design and the Aerospace Development Group (GDAe). The expected outcome is the generation of technical data to support decision-making in academic and institutional rocketry projects, contributing to the consolidation of best practices in propulsion engineering within the Brazilian aerospace context.

### 2.1. Materials and Methods

The base formulation for both manufacturing methods was the composition known as KNSU, in the following mass ratio:

- **65% Potassium Nitrate (KNO<sub>3</sub>):** Used as the oxidizer, finely ground to increase surface area.
- **35% Sucrose (C<sub>12</sub>H<sub>22</sub>O<sub>11</sub>):** Used as the fuel and binder. For the pressing method, refined sucrose (confectioner's sugar) was used; for the melting method, commercial granulated sucrose was used.

The motor casing was constructed using standard brown PVC pipes for plumbing installations.

### 2.2. Propellant Grain Manufacturing

#### 2.2.1. Method by Thermal Melting (Hot-Melt)

The manufacturing process for the melt-cast grain followed these steps:

1. 15.73 g of KNO<sub>3</sub> and 8.47 g of sucrose were weighed, totaling 24.2 g. This value includes a 10% margin to compensate for material losses during the process.
2. The components were added to a non-stick metal container with a small amount of water for dissolution and homogenization, mitigating the risk of premature ignition.
3. The mixture was heated on an electric hot plate (never a gas stove, for safety), under constant stirring, until it reached caramelization and a homogeneous paste-like consistency, with a color similar to dulce de leche. The average preparation time was 10 minutes.
4. The propellant paste was poured into a cylindrical mold, previously lubricated and internally lined with paper, for subsequent insertion into the PVC tube.

#### 2.2.2. Method by Cold Pressing

The process for the pressed grain was as follows:

1. 14.3 g of  $\text{KNO}_3$  and 7.7 g of refined sucrose were weighed, totaling 22 g of propellant per motor.
2. The dry components were thoroughly mixed until a uniform color and texture were achieved.
3. The mixture was transferred into the PVC motor tube.
4. Compaction was performed using a manual hydraulic press (car jack type), applying constant force for 30 seconds to form the propellant grain directly inside the motor casing.

### 2.3. Motor Design and Assembly

The motor design was standardized for both methods. The motor casing was constructed using a standard brown PVC pipe with a length of 100 mm, an external diameter of 20 mm, and a wall thickness of 2 mm. The ends were closed with PVC caps. For the cold pressed propellant motors, a small portion at the bottom of the forward cap was filled with aluminum foil to act as a protective bulkhead. The critical dimensions, detailed in the technical drawing in Figure 1, are:

- Nozzle Throat Diameter: 6 mm
- Core Diameter: 8 mm

The final masses of the loaded motors, whose components and final assembly are illustrated in Figure 2, were:

- Hot-Melt Motors: Masses of 45.9 g, 44.0 g, and 46.3 g.
- Cold-Pressed Motors: Standardized mass of 56.0 g each (with 22 g of propellant).



**Figure 1.** Technical drawing of the experimental motor. Source: Author.



(a)



(b)

**Figure 2.** Components and final assembly of the experimental motor. (a) PVC motor casing. (b) Finalized and loaded motor. Source: Author.

### 2.4. Static Test Stand Configuration

Two test stand configurations were used for thrust data acquisition (Figure 3):

- Cold-Pressed Tests: A test stand with one 50 kg load cell, an operational amplifier, and an oscilloscope for data logging was used.
- Hot-Melt Tests: A test stand with two 50 kg load cells in parallel for greater robustness, an HX711 amplifier, and an ESP32 microcontroller for data acquisition and processing was used.



(a)



(b)

**Figure 3.** Configurations of the static test stands used. **(a)** Data collection in an outdoor environment. **(b)** Test stand for the hot-melt propellant tests. Source: Author.

## 2.5. Experimental Procedure and Safety Measures

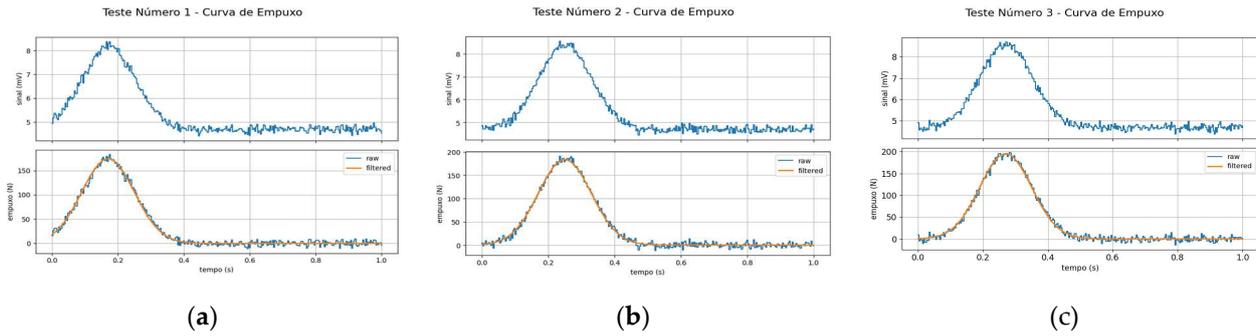
All tests followed a strict safety and logging protocol:

1. The motor was positioned and secured on the test stand in an open, isolated location with the nozzle pointed in a safe direction.
2. Ignition was performed remotely via an electrical system.
3. During each test, the following were recorded: thrust over time (generating a graph), burn time (via video analysis), and the post-burn structural integrity of the motor.
4. The initial and final masses of the motor were collected for each test.
5. Safety measures were strictly observed, including the use of Personal Protective Equipment (PPE), such as gloves with thermal protection.
6. The propellant grains were stored in airtight containers with silica gel to prevent moisture absorption.

## 3. Results and discussion

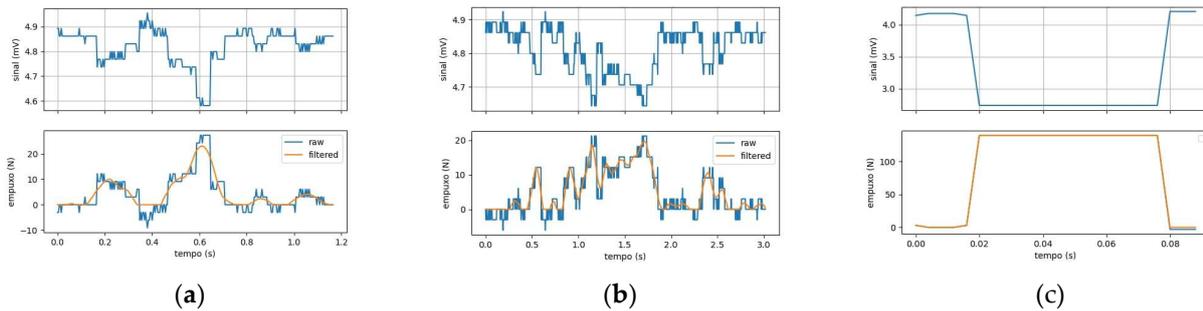
### 3.1. Tests of the Melt-Cast Propellant (Hot-Melt)

The data were plotted and analyzed as indicated by Sutton and Biblarz (2010). The tests with the propellant manufactured by thermal melting were characterized by high and rapidly occurring thrust peaks, suggesting a significantly high burn rate. The maximum thrust peaks recorded for the three tests were 174 N, 183 N, and 195 N. These values, obtained from motors with an average mass of 45.4 g, indicate a propellant with high energy density; however, the sharp nature of the peaks suggests a potentially more aggressive combustion. The corresponding thrust curves are shown in Figure 4.



**Figure 4.** Thrust curves for the three tests of the melt-cast propellant. **(a)** Test 1. **(b)** Test 2. **(c)** Test 3. Source: Author.

Static tests performed on the 56 g cold-pressed propellant motors revealed significant performance inconsistency and structural integrity issues. The initial test (Figure 5a) demonstrated a stable burn profile over 2.66 s, yielding a maximum thrust of 21.7 N and a total impulse of 16.0 Ns. This corresponds to a specific impulse ( $I_{sp}$ ) of 29.1 s, a modest but acceptable result. In contrast, a subsequent test (Figure 5b) showed a markedly shorter burn time of only 0.944 s and a diminished impulse of 5.1 Ns, indicating probable combustion instability or a premature burnout. The final trial (Figure 5c) resulted in a catastrophic failure early in the burn. Analysis suggests that internal pressure exceeded the grain’s structural limit, causing it to fracture. This drastically increased the available surface area for combustion, leading to a violent and uncontrolled over-pressurization event that registered a thrust spike of 140 N, far exceeding the motor casing’s design limits.

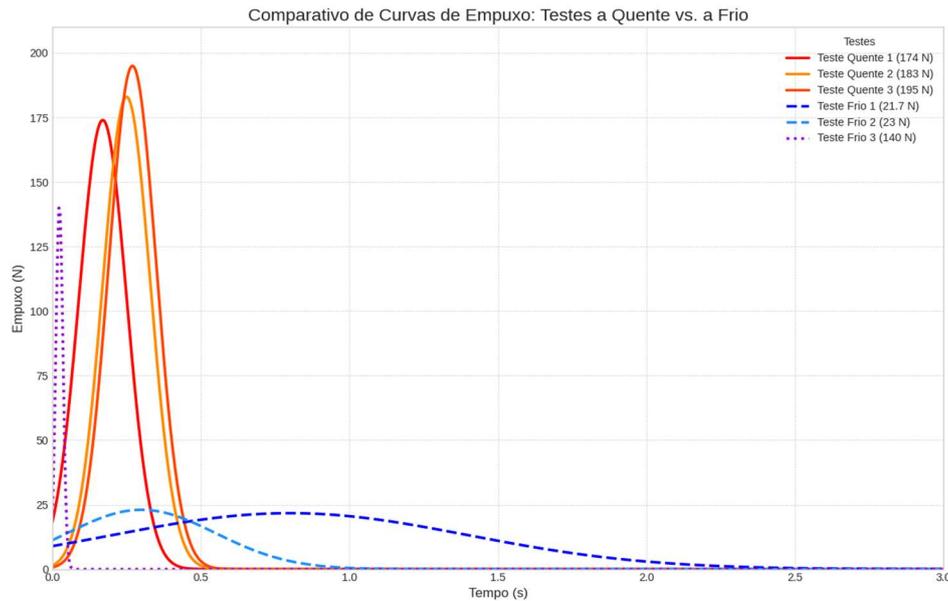


**Figure 5.** Thrust curves for the three tests of the cold-pressed propellant. **(a)** Test 1 (Stable burn). **(b)** Test 2 (Unstable burn). **(c)** Test 3 (Structural failure). Source: Author.

### 3.2. Comparative Analysis and Discussion

The comparative analysis of the two propellant manufacturing methodologies unequivocally highlights a pronounced trade-off between propulsive performance and operational reliability. The thermal melting method consistently yields a high performance propellant, characterized by thrust peaks that are approximately an order of magnitude (nearly 10 times) greater than the stable, sustained burn achieved with the cold pressed propellant. This significant difference underscores the superior energetic output and rapid combustion kinetics inherent to the thermally processed material. Conversely, the cold-pressing method, while offering distinct advantages in terms of handling safety and manufacturing simplicity, exhibited a critical vulnerability to stochastic manufacturing inconsistencies.

These inherent variabilities frequently manifested as both substantial performance heterogeneity and, more critically, catastrophic structural failures within the propellant grains. The paramount risk associated with the pressed grain lies precisely in its inherent unpredictability, which compromises both its consistent functional output and its structural integrity under operational conditions.



**Figure 6.** Comparison of the thrust curves for the hot-melt and cold-pressed propellants. Source: Author.

The graphical visualization in Figure 6 makes this performance disparity unequivocal. It is evident that the curves for the hot-melt tests (solid lines) are clustered in a region of high thrust and predictable behavior. In contrast, the curves for the cold-pressed tests (dashed lines) demonstrate not only a lower magnitude of force but also significant dispersion and unpredictability, culminating in a failure profile in the third test. This variability is a critical factor in the risk assessment for the rocket's mission.

#### 4. Discussion

This work conducted a comparative analysis of the performance of solid propellants based on potassium nitrate ( $\text{KNO}_3$ ) and sucrose ( $\text{C}_{12}\text{H}_{22}\text{O}_{11}$ ), manufactured by thermal melting and cold pressing. The static tests demonstrated critical differences between the methods. The propellant produced by thermal melting showed far superior ballistic performance, with peak thrusts reaching 195 N, indicating a high energy density. In contrast, the cold-pressed propellant, although it achieved a stable burn in one of the tests with an average thrust of 6.03 N, proved to be a fundamentally unreliable method.

The main conclusion is that a direct trade-off exists between performance and reliability. The cold-pressing method, despite being operationally simpler and safer during manufacturing, resulted in propellants with high performance variability and susceptibility to catastrophic structural failures. Such unpredictability represents a significant risk to the vehicle's integrity. The thermal melting method, in turn, produced a consistently more powerful propellant, the application of which would demand a robust motor design capable of withstanding the high pressures generated.

Therefore, for experimental rocketry purposes where safety and repeatability are prioritized, the cold-pressing method would only be viable with the implementation of rigorous quality control and non-destructive inspection of the grains. Suggested future work includes the investigation of polymeric binders to increase the structural integrity of the pressed grains and a more detailed characterization of the melt-cast propellant's thrust curve.

**Funding:** This research received no external funding.

**Acknowledgments:** We acknowledge the Northeast Aerospace Federation (FAERNE) for their institutional and logistical support in conducting the experiments, as well as the participating educational institutions for fostering applied academic research in aerospace engineering. We also extend our gratitude to Sirius Rockets, Cactus Rockets Design, the Aerospace Development Group (GDAe), and Potiguar Rocket Designers (PRD), whose dedication was essential to consolidating the results presented here. We thank Professor Dr. Carlos Alberto Rios Brito Júnior for his logistical support. We also thank LABESE (Laboratory of Electronics and Space Embedded Systems) and the Aldebaran mission for their structural and institutional support.

**Conflicts of Interest:** The authors declare no conflict of interest.

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