# Temperature Measurement of Ballistic Evaluation Motor Using K-Type Thermocouple

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ABSTRACT

*The paper presents an investigation of the burning rate of the selected solid propellant using a Ballistic Evaluation Motor (BEM) for solid-rocket propulsion study. A K-type thermocouple was used to capture the temperature of the BEM. Previous studies on BEM have been customized to specific experiments accordingly without any standardized approach for temperature measurement. Variations in the methodology have led to inconsistent and potentially unreliable results across different research efforts. The purpose of the study is to establish a more reliable and standardized method for temperature measurement in BEM by validating the temperature readings recorded by a K-type thermocouple. The scope of the study includes recording the ignition and combustion temperature of the BEM against the time. Three different propellants were used in the experiments, ammonium perchlorate with sorbitol and magnesium, potassium nitrate with sucrose, and ammonium perchlorate with sorbitol and iron (III) oxide. The results indicate that ammonium perchlorate with sorbitol gives the highest maximum temperature which is at 101℃. The other propellants, ammonium perchlorate with magnesium and potassium nitrate with sucrose, recorded maximum temperatures of 75.20 °C and 57.25 °C, respectively. The validation process confirmed the reliability of the K-type thermocouple, with an average deviation of 2.3 °C to 3.7 °C from the reference thermometer readings. A notable performance was observed for the propellant using sorbitol and*

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*ammonium perchlorate with iron (III) oxide. The experiment contributes to significant findings of the solid-rocket propulsion study, hence advanced solid-rocket research can be explored from here onwards.*

**Keywords:** *BEM; Propellant; Temperature; Thermocouple*

## Introduction

Tejasvi et al. [1] emphasized the role of Ballistic Evaluation Motor (BEM) as an analogue of large-scale rocket engines. The test serves as a static model subjected to analyzing the performance of a solid rocket propellant in terms of the burning rate, thrust, and specific impulse of the motor. The burning rate refers to the rate of burning of the propellant over a period. This performance is closely related to the pressure and the heat inside the combustion chamber as the combustion of propellant occurs [2]. BEM also helps in understanding the effect of pressure and temperature on the burning rate of a solid propellant rocket motor. [3]. Deluca et al. also mention the importance of the burning rate as well as the effect of pressure in designing the rocket and its fuel itself [4]. BEM is also done to make sure that the solid composite propellant used conforms to the chemical composition and ease of processing [5]. Aside from the temperature and pressure inside the combustion chamber, it is also found that the burning rate of solid propellant is affected by the flame regression which refers to the regression of the propellant surface that is exposed to the flame during the combustion process [6]. Faster flame regression corresponds to a greater burning rate which will then increase the thrust of the rocket motor.

In order to record the temperature measurement during the BEM testing, K-type thermocouples are deemed to be a suitable instrument. This type of thermocouple is widely utilized in industries, laboratories, and research due to its reliability and excellence in measuring temperature in hard-to-reach places such as the combustion chamber. Due to the advancement of technology, K-type thermocouple is used due to its accuracy and dependability, which is great for engine testing and scientific studies. Despite its reliability and efficiency, K-type thermocouples from manufacturers were not calibrated which would affect the performance of the thermocouples. Therefore, calibrations are needed to make sure a comparative analysis with high-quality thermocouples is obtained within the context of a real rocket motor experiment [7].

A static test done at the Hydraulic Machines Laboratory (LMH) at the Federal University of Parana (UFPR) using horizontal positioning of a rocket motor utilizes K-type thermocouples on the outer wall of the combustion chamber in order to measure the exterior temperature of the solid motor rocket [8] further proves the availability of K-type thermocouples in BEM testing.

This study aims to calibrate K-type thermocouples in order to achieve precise temperature measurement as well as accurately measure the temperature inside the combustion chamber during the BEM testing using easily accessible and available thermocouples.

## Methodology

### Calibration

A basic calibration process often involves using hot water as a medium to calibrate a thermometer and a K-type thermocouple. This process involves adjusting a thermocouple's measurement of boiling water's temperature by comparing it to a thermometer's reading. This would help in ensuring that future temperature measurements will be precise and reliable across different temperature ranges.

### K-type thermocouple with MAX6675 amplifier

K-type thermocouples are deemed to be suitable for the measurement of temperature during BEM evaluation as it is ideal for a wide range of temperatures. K-type thermocouples usually comes with a positive part that's not magnetic and a negative part that is. These thermocouples often use Nickel, a metal that handles high temperatures well. Vicentin et al. [9] proved that a K-type thermocouple is popular because it is versatile, works across a wide range of temperatures, is sensitive, and also cost-effective. Therefore, it is found that in order to effectively understand the elucidation of K-type thermocouples as well as their control variables and develop a complete model through numerous studies and data collection.

K-type thermocouples were deemed suitable for measuring BEM due to their several significant advantages over other thermocouples, including the ability to perform in a variety of atmospheric and harsh environmental conditions. The working principle for the thermocouple is that they measure generated thermoelectric voltage (Electromotive Force: EMF), in order to form a thermocouple [10]. They offered good EMF linearity for temperature measurement as well as produced reliable results, not to mention being cheaper than other thermocouples [11]. The temperature measurement in the BEM was conducted through an experimental setup employing an Arduino interface and an MAX6675 thermocouple. Any microcontroller could easily measure temperatures ranging from 0 °C to 1024 °C by utilizing the MAX6675 breakout board and a K-type thermocouple. The Serial Pheripheral Interface (SPI) was used to transmit the chip's output data. SPI pins were used in this instance using the Arduino Uno board. The reason for selecting MAX6675 from various options was its wide measurement range, enabling temperature readings from 0 °C to 1024 °C at the hot junction [12].

## Experiment Setup

### Propellant

The first step in fabricating the propellant was the material selection for the motor. Mild steel was chosen for the rocket motor casing while cylindrical shape was chosen for design simplicity. As there were 3 different propellants used, each motor was made at a constant propellant mass of 100 g. This would act as the controlled variable which helped ensure consistency in getting the result. Table 1 shows the composition of the propellant used for each test.

Table 1: Compositions of propellants used

| Composition | Percentage weightage (%) |
|---|---|
| Test 1 | |
| Ammonium perchlorate ($NH_4ClO_4$) | 76.5 |
| Sorbitol ($C_6H_{14}O_6$) | 22 |
| Magnesium (Mg) | 1.5 |
| Test 2 | |
| Potassium nitrate (KNO3) | 65 |
| Sucrose ($C_{12}H_{22}O_{11}$) | 35 |
| Test 3 | |
| Ammonium perchlorate ($NH_4ClO_4$) | 74.5 |
| Sorbitol ($C_6H_{14}O_6$) | 25 |
| Iron (III) oxide ($Fe_2O_3$) | 0.5 |

### Nozzle

For the rocket nozzle, a PVC pipe was used, acting like a cartridge and container for the nozzle. The design of both the nozzle and its corresponding base is accomplished utilizing a computer-aided design tool known as CATIA. Subsequently, this design is transmitted to a 3D printer, which generates the actual mold through a process referred to as 3D printing. The nozzle mold is positioned 4 mm away from both the front and back of the nozzle. A smaller throat diameter would raise the pressure drop in the nozzle, which boosts combustion and makes the propellant burn faster. This would then increase the speed of the gases from combustion and help them mix well with the propellant that hasn't burned yet.

### Igniter

Two wires with a short piece of special wire called nichrome are soldered to it to produce the igniter used. Black powder, made up of 75% potassium nitrate, 15% charcoal, and 10% sulphur was used as the ignition powder charge. To increase safety precautions, the end of the exposed wires was twisted together to prevent any accidental shock that could lead to ignition. Four 1.25 V nickel-cadmium batteries are used to supply power from the electrical power box.

### Data analysis

In order to accurately measure the temperature while propellant burns, a K-type thermocouple was utilized. This sensor proved effective for handling high temperatures accurately. The MAX6675 amplifier was also used to amplify the signal from the thermocouple. This amplifier acts like a converter, making the signal ready for processing by other parts. An Arduino microcontroller takes the data from the sensor and performs various tasks using the data collected. This microcontroller can be programmed to do different tasks, including handling data. Once the data was processed, it was sent to a laptop for display and data storage.

## Results and Discussion

### Calibration of K-type thermocouples

Septiana et al. [13] found that thermocouples are an essential temperature measurement device, but they would require calibration in order to produce accurate and interpretable data. Temperature stands as a pivotal factor across all facets of existence, underscoring the necessity for precise temperature assessment. Researchers are currently employing K-type thermocouples and MAX6675 sensors to measure temperature values. However, Kumar et al. [14] mentioned that it is essential to calibrate these sensors before use, as they may not offer precise readings for temperature measurements spanning from ambient conditions to boiling water temperatures.

Thermocouples need to be calibrated to produce interpretable measurement information. This calibration process typically involves utilizing hot water as a medium to calibrate both a thermometer and a K-type thermocouple.

When examining the calibration graph in Figure 1, it becomes evident that the thermocouple and thermometer exhibit closely accurate measurements. The temperature differences between the thermometer and K-type thermocouple begin at the same temperature which is 33 °C. As the time increases, the deviation of measurement becomes larger until 5 s. After 5 s, the deviation between the measurement of the K-type thermocouple and the thermometer decreases until the end of the experiment. It is found that the average deviation between the devices is comparable with each other, showing consistent and reliable results.

The calibration graph reveals a remarkable level of agreement between the thermocouple and thermometer, indicating a closely accurate correlation in their temperature readings.

The close alignment of data points on the graph demonstrates the consistency and reliability of both instruments in measuring temperature. The minimal deviation between the thermocouple and thermometer readings further validates their precision and reinforces confidence in their calibration.

This high degree of accuracy observed in the calibration graph highlights the effectiveness of both the thermocouple and thermometer in capturing temperature variations with exceptional consistency. The reference used for accuracy needs to match or be even better than the instrument being tested. When calibrating a thermocouple, a precise thermometer or an alternate thermocouple is a good choice [15]. This calibration process builds confidence in the accuracy of the measurements, enhancing the reliability and credibility of temperature data collected in scientific research, industrial processes, and other temperature-sensitive applications.

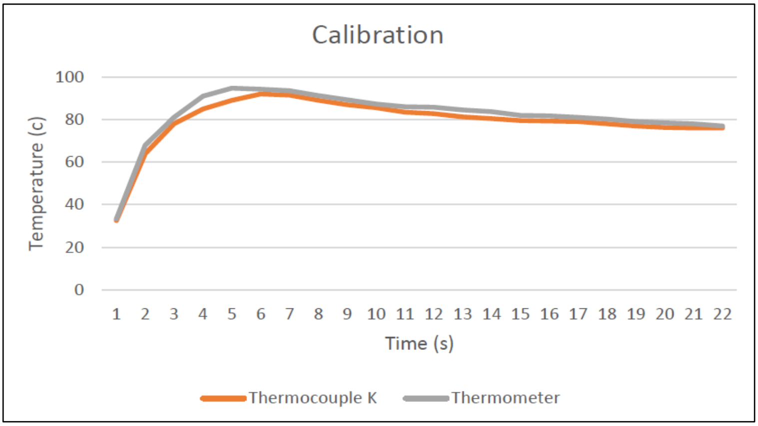


Figure 1: Temperature vs. time for calibration

## Temperature of BEM

A testing process involves gathering temperature and time data using the Arduino microcontroller with the K-type thermocouple and the MAX6675 amplifier. These data sources are essential for monitoring and recording crucial information during testing. Figure 2 illustrates the condition of the BEM and K-type thermocouple with the igniter during combustion.

The initial propellant test combines sorbitol ($C_6H_{14}O_6$) at 22%, ammonium perchlorate ($NH_4ClO_4$) at 76.5%, and 1.5% magnesium (Mg). The highest temperature reached, according to Table 2, is 75.20 °C at 12 s.

Sorbitol serves as the fuel, burning to release heat and gases. Ammonium perchlorate provides oxygen for combustion, breaking down into oxygen gas ($O_2$), nitrogen gas ($N_2$), water vapor ($H_2O$), and energy. Magnesium, added to the propellant, heightens energy output. When ignited, magnesium reacts with ammonium perchlorate's oxygen, producing magnesium oxide (MgO) and more energy. The propellant's ignition leads to combustion reactions for sorbitol and ammonium perchlorate. Sorbitol oxidizes, releasing carbon dioxide ($CO_2$), water ($H_2O$), and heat. Ammonium perchlorate gives oxygen for combustion and decomposes, releasing gases and energy. Magnesium boosts the combustion, therefore increasing the energy release.

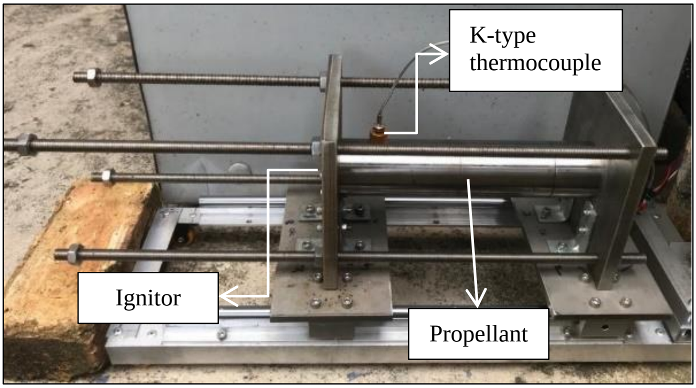


Figure 2: BEM combustion setup

Table 2: Test 1 for ammonium perchlorate with sorbitol and magnesium

| **Propellant composition (gr)** | **Time (s)** | **Temperature (°C)** |
|---|---|---|
| 22% Sorbitol ($C_6H_{14}O_6$), 76.5% Ammonium Perchlorate ($NH_4ClO_4$), 1.5% Magnesium (Mg) | 2 | 28.75 |
| | 4 | 37.75 |
| | 6 | 49.00 |
| | 8 | 56.25 |
| | 10 | 67.25 |
| | 12 | 75.20 |
| | 14 | 69.75 |
| | 16 | 67.75 |
| | 18 | 65.50 |
| | 20 | 62.00 |
| | 22 | 61.75 |
| | 24 | 60.25 |
| | 26 | 59.75 |
| | 28 | 59.25 |
| | 30 | 57.50 |

The second test uses potassium nitrate ($KNO_3$) at 35% concentration and sucrose ($C_{12}H_{22}O_{11}$) at 65%. The highest temperature recorded in Table 3, is 57.25 °C at 10 seconds. Potassium nitrate supplies the oxygen needed for the combustion process, breaking down into oxygen gas ($O_2$) and nitrogen gas ($N_2$) to support fuel burning.

Table 3: Test 2 for potassium nitrate and sucrose propellant

| Propellant composition (gr) | Time (s) | Temperature (°C) |
|---|---|---|
| 35% Potassium Nitrate ($KNO_3$), 65% Sucrose ($C_{12}H_{22}O_{11}$) | 2 | 26.50 |
| | 4 | 31.50 |
| | 6 | 37.50 |
| | 8 | 49.25 |
| | 10 | 57.25 |
| | 12 | 55.25 |
| | 14 | 53.25 |
| | 16 | 49.75 |
| | 18 | 47.25 |
| | 20 | 44.25 |
| | 22 | 39.75 |
| | 24 | 38.25 |
| | 26 | 37.50 |
| | 28 | 37.25 |
| | 30 | 36.50 |

When potassium nitrate ($KNO_3$) reacts with a fuel like sucrose ($C_{12}H_{22}O_{11}$), a reaction happens as in Equation (1):

$$C_{12}H_{22}O_{11} + 6KNO_3 \text{ -> } 12CO_2 + 11H_2O + 3N_2 + 6K_2O \qquad (1)$$

This reaction shows the combustion of sucrose with potassium nitrate, resulting in the production of carbon dioxide ($CO_2$), water ($H_2O$), nitrogen gas ($N_2$), and potassium oxide ($K_2O$). The combustion reaction of sucrose with $KNO_3$ is highly exothermic, meaning it releases a significant amount of heat. The high concentration of oxygen in the $KNO_3$ molecule allows for efficient combustion of the fuel, leading to higher temperature and energy release.

The final test used ammonium perchlorate ($NH_4ClO_4$) (74.5%), sorbitol ($C_6H_{14}O_6$) (25%), and iron (III) oxide ($Fe_2O_3$) (0.5%) as shown in Table 4. The highest temperature the sensor measured was 101.00 °C at 12 s.

As ammonium perchlorate goes through combustion, it releases a significant amount of oxygen, making it an effective oxidizer. Sorbitol is a fuel mixed with ammonium perchlorate to make solid propellants. It adds energy but does not undergo oxidation. Iron (III) oxide also known as rust, is the catalyst for the propellant. It enhances the combustion process, promoting improved and accelerated burning, leading to heightened thrust and energy release in engines. Additionally, it aids in stabilizing the burn and minimizing residual waste.

Table 4: Test 3 for ammonium perchlorate with sorbitol and iron (III) oxide propellant

| Propellant composition (gr) | Time (s) | Temperature (°C) |
|---|---|---|
| 25% Sorbitol ($C_6H_{14}O_6$), 74.5% Ammonium Perchlorate ($NH_4ClO_4$), 0.5% Iron (III) Oxide ($Fe_2O_3$) | 2 | 26.75 |
| | 4 | 33.00 |
| | 6 | 48.25 |
| | 8 | 68.75 |
| | 10 | 85.00 |
| | 12 | 101.00 |
| | 14 | 98.75 |
| | 16 | 98.25 |
| | 18 | 97.50 |
| | 20 | 96.75 |
| | 22 | 95.50 |
| | 24 | 94.25 |
| | 26 | 94.00 |
| | 28 | 93.75 |
| | 30 | 92.75 |

The graph in Figure 3 shows the results of burning three different propellant types in the BEM. At the beginning, the temperature goes up quickly, showing the motor igniting and propellant burning. Elghafour et al. [16] found that this encounters the flame zone, where a high flame temperature prevails. This zone is crucial for the formation of final combustion products where the combustion products reach a thermal equilibrium state. The peak temperature changes based on the propellant, motor, and conditions inside the combustion chamber such as the pressure. After the peak the temperature levels off or changes slowly. This means steady burning is happening, with heat being made and lost. Then, the temperature slowly goes down as the propellant is used up and burning slows. Eventually, the temperature drops to a low point, called the burnout temperature. This is when the propellant is all used up and burning stops.

The highest temperature recorded in Figure 3 is on test 3. The propellant includes ammonium perchlorate ($NH_4ClO_4$), sorbitol ($C_6H_{14}O_6$), and iron (III) oxide ($Fe_2O_3$). Ammonium perchlorate is often used as a strong oxidizer in rockets because it has lots of oxygen and is stable. It is widely used in propellants and explosives for its effectiveness. These materials usually experience high pressure and heat during burning and explosions. Venugopalan [17] mentioned that by incorporating various potential oxidizers like potassium nitrate or ammonium perchlorate, it becomes possible to increase the combustion temperature or pressure. Iron (III) oxide helps the fuel burn completely and quickly, making the process more effective and producing more energy. Patil et al. [18] stated that iron (III) oxide acts as a catalyst, making the reactions happen faster and more efficiently. It accomplishes this by accelerating the reactions without undergoing depletion itself. The higher concentration of $Fe^{3+}$ ions where ammonium perchlorate and the fuel meet is because of strong interactions between ions. This concentrated catalyst helps the fuel and oxidizer vapors break down more easily, making the reactions hotter and more intense. The extra heat then leads to a faster burning rate.

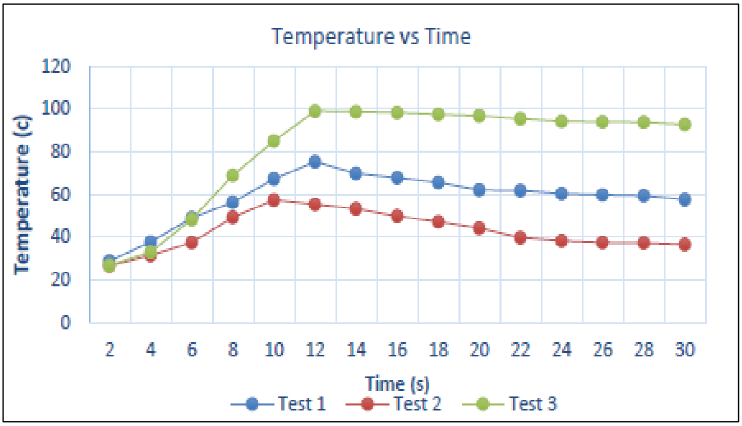


Figure 3: Graph temperature vs time for three different propellants

On the other side, test 2 had the lowest temperature using a mix of potassium nitrate ($KNO_3$) and sucrose. This combination forms a propellant, but it generally has less oxidizing power compared to the mix of ammonium perchlorate and sorbitol. Potassium nitrate gives oxygen for burning, and sucrose is the fuel. Based on the previous research, Henry et al. [19] found that although potassium nitrate can oxidize, it's not as strong as ammonium perchlorate in terms of oxygen content and release.

In the case of a Ballistic Evaluation Motor (BEM) burning, Crawford et al. [20] proved that achieving high reaction rates can be facilitated by elevating the combustion temperature, enhancing thermal conductivity, and or operating at higher pressure levels within the rocket motor. Higher heat of combustion means more energy released, which can make the combustion chamber hotter. The heat of combustion measures how much energy is released when a certain amount of fuel burns. This can raise temperatures in the combustion chamber. The temperature depends on factors like the heat of combustion, how well the reaction happens, and motor design. It's important to remember that higher temperatures might affect the motor's structure and performance. Too much heat can damage materials or have other bad effects.

## Conclusions

Based on the results of the calibration graph and considering the discussed factors, the thermocouple proves its ability to accurately measure temperatures within a specific range. The calibration process and data analysis increase our confidence in the recorded temperatures. Results from the calibration show accurate correlation and consistency of temperature measurement. The K-type thermocouple can endure high temperatures and react quickly, making it ideal for Ballistic Evaluation Metal (BEM). Ammonium perchlorate with sorbitol and iron (III) oxide gives the highest maximum temperature of 101℃ while potassium nitrate and sucrose propellant give the lowest maximum temperature of 57.25 ℃. This shows that ammonium perchlorate with sorbitol and iron (III) oxide are able to release higher energy compared to the other 2 propellants. Iron (III) oxide as the catalyst enhances the combustion process, promoting improved and accelerated burning, leading to heightened thrust and energy release in engines.

## Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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## Conflict of Interests

All authors declare that they have no conflicts of interest.

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