

Effect of Activated Carbon on the Combustion Characteristics of Magnesium–Sodium Nitrate Propellants

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ABSTRACT

Magnesium–nitrate-based propellant systems represent an alternative class of solid propellants whose combustion characteristics can be modified through composition and the use of additives. This study aims to evaluate the effect of activated carbon addition on the burning rate and combustion energy of magnesium–sodium nitrate-based propellants. Propellant samples were prepared in two compositional variations, namely NaNO_3/Mg and NaNO_3/Mg with activated carbon addition. The burning rate was measured experimentally with five replicates ($n = 5$), while the calorific value was determined using a bomb calorimeter. Differences in burning rate were analyzed using Welch's t -test at a significance level of $\alpha = 0.05$. The results show that the addition of activated carbon significantly reduces the burning rate of the propellant ($p < 0.001$). In contrast, the calorific value increased from 2395 cal g^{-1} to 2617 cal g^{-1} . These findings indicate that activated carbon modifies the combustion characteristics and contributes to the energetic properties of the system, suggesting its potential application for burning rate control in magnesium–sodium nitrate-based propellants.

Introduction

Solid propellants are energetic materials that, through combustion, are capable of generating large volumes of gas within a short period of time. This property makes solid propellants widely used as sources of thrust or propulsion in various systems, both military and civilian, that require rapid and controlled energy release [1]. In solid rocket propulsion systems, propellants generally consist of three main components, namely a fuel, an oxidizer, and a binder. The fuel serves as the primary source of energy, the oxidizer supplies the oxygen required to sustain the combustion reaction, while the binder functions to bind all components together and simultaneously contributes to the overall energy content of the propellant [2]. Ammonium perchlorate (NH_4ClO_4 , AP) is still widely used as an oxidizer in solid rocket propellants due to its

high combustion performance. However, the combustion of AP-based propellants produces hazardous substances that pose negative impacts on human health and the environment, thereby motivating research into the development of alternative oxidizers through compound synthesis or modification [1]. One alternative that has been considered is nitrate-based oxidizers, which offer good availability from local sources, relatively low cost, and advantages over perchlorate compounds in terms of environmental impact [3]. In addition, nitrate-based oxidizers have been widely used in magnesium–nitrate propellant systems and have been reported to support the combustion process through oxidizer decomposition mechanisms [4]. Based on these considerations, sodium nitrate (NaNO_3) was selected in this study as the oxidizer to represent the

magnesium–nitrate–based propellant system under investigation.

In magnesium–nitrate–based propellant systems, magnesium (Mg) acts as the fuel and undergoes oxidation during the combustion process. This oxidation reaction is exothermic and releases a large amount of thermal energy, allowing the combustion to proceed in a stable manner. At high temperatures, magnesium oxide (MgO) is formed as the primary oxidation product [4].

The combustion performance of solid propellants is evaluated through parameters that represent their energetic characteristics and combustion stability. The burning rate is one of the most important parameters, as it is directly related to the rate of energy release and the stability of combustion within the rocket motor [5]. In addition, the calorific value is used to describe the energetic properties of solid propellants and energetic materials, as its measurement method is relatively simple and provides good accuracy [6]. The determination of the combustion energy of solid materials is commonly carried out using the bomb calorimeter method, which is a constant-volume calorimetric technique that measures the thermal energy released during combustion in a closed system [7]. Natural variations in the burning rate of solid propellants, which are influenced by physical, mechanical, and chemical factors, make statistical analysis essential for obtaining representative data [8].

Carbon-based materials, such as charcoal and carbon black, are often used as additives in nitrate-based combustion systems to modify combustion characteristics. Carbon materials with high surface area can enhance contact between the fuel and the oxidizer, thereby influencing the burning rate and reaction energy [9]. However, the effect of carbon addition on combustion characteristics does not always exhibit a uniform trend, as it depends on the physical properties of the carbon, such as surface area and reactivity, which influence its interaction with the oxidizer as well as the reaction mechanisms during combustion [10]. Specifically, studies on the effect of activated carbon addition in magnesium–nitrate propellant systems remain limited in the literature.

Resin is used as a binder to maintain the homogeneity of the propellant mixture and to enhance its physical stability. The presence of a binder has also been reported to support more stable combustion without causing significant negative effects on the combustion energy of the propellant [3]. Therefore, in this study, the resin was used in the same amount for all samples and was not treated as an experimental variable. This study aims to evaluate the effect of activated carbon addition on the burning rate and combustion energy of magnesium–nitrate–based propellants.

This study provides a systematic evaluation of activated carbon as a combustion modifier in Mg–NaNO₃ composite propellants. The primary contribution lies in demonstrating the dual effect of activated carbon on combustion behavior, namely the reduction of burning rate alongside an increase in calorific value. By integrating quantitative burning rate measurements with thermochemical analysis, this work clarifies the functional role of carbon additives in nitrate-based propellant systems.

Materials and Methods

Materials

The chemicals used in this study were sodium nitrate (NaNO₃, p.a., 99.5% purity) as the oxidizer, magnesium powder (Mg, p.a., 99% purity, particle size 0.1–0.3 mm) as the metallic fuel, and activated carbon (AC) with a surface area greater than 500 m² g^{−1} and a carbon content of 80% as an additive. Unsaturated polyester resin (density 1.1 g cm^{−3}) was used as the binder, with methyl ethyl ketone peroxide (MEKP) employed as the curing catalyst at a concentration of 2% w/w. Acetone (C₃H₆O, p.a.) was used for cleaning laboratory equipment.

The selection of materials was based on their availability from local sources as well as the suitability of their physical and chemical properties for composite propellant formulation. All chemicals were obtained from reliable suppliers and used without further pretreatment unless otherwise specified.

Instruments

This study employed standard laboratory equipment for sample preparation and characterization. The main instruments

used included an analytical balance (Mettler Toledo ME204), a mechanical mixer (IKA RW 20), a hot plate equipped with a magnetic stirrer (IKA RCT Basic), silicone molds with dimensions of 1 cm × 1 cm × 1 cm, alcohol burner, a bomb calorimeter (IKA C2000 series), and standard laboratory glassware.

Experimental Procedure

The experimental procedure began with the mixing of the propellant raw materials. For samples without activated carbon (AC) addition, sodium nitrate (NaNO₃, p.a., 99.5% purity) and magnesium (Mg, p.a., 99% purity) were mixed at a mass ratio of 50:50. Meanwhile, for samples with activated carbon (AC) addition, having a surface area greater than 500 m² g⁻¹ and a carbon content of 80%, the composition used was NaNO₃:Mg:AC with a mass ratio of 40:40:20.

All solid components were mixed using an IKA RW 20 mechanical mixer for 5 minutes until a homogeneous mixture was obtained. After mixing the solid materials, unsaturated polyester resin (density 1.1 g cm⁻³) was added to the mixture as a binder, followed by the addition of methyl ethyl ketone peroxide (MEKP) catalyst at 2% by weight relative to the resin mass. The mixture was then stirred at 80 °C for 10 minutes using a hot plate equipped with a magnetic stirrer (IKA RCT Basic) to ensure the uniform distribution of the binder throughout the components.

The homogeneous propellant mixture was then cast into silicone molds with dimensions of 1 cm × 1 cm × 1 cm. The curing process was carried out by allowing the samples to remain at room temperature for 24 hours until solid propellant specimens were formed. The cured propellant samples were subsequently used for combustion characteristic testing.

Burning Rate Test

The burning rate test was conducted to determine the flame propagation velocity on solid propellant samples. Propellant specimens with dimensions of 1 cm × 1 cm × 1 cm were positioned vertically on a heat-resistant holder and ignited at one end using an alcohol flame until stable combustion was achieved. The

combustion time (Δt) was recorded using a stopwatch from the moment the flame began to propagate along the sample surface until it reached the opposite end of the specimen.

The burning rate (r) was calculated as the ratio of the burned sample length (L) to the combustion time (Δt), as expressed in Equation (1) [11]:

$$r = \frac{L}{\Delta t} \quad (1)$$

where r is the burning rate (cm s⁻¹), L is the burned sample length (cm), and Δt is the combustion time interval (s). In this study, the value of L was fixed at 1 cm. Each compositional variation was tested with five replicates to obtain representative data.

The burning rate measurements were conducted under open-air conditions at atmospheric pressure (1 atm) and ambient temperature. The reported values therefore represent surface burning rates under ambient conditions rather than confined motor conditions.

Statistical Analysis

Statistical analysis was performed to evaluate differences in the burning rate between propellants without and with activated carbon addition. Each compositional variation was tested with five replicates ($n = 5$), and the data are presented as mean $\pm$ standard deviation (SD). The assumptions of normality and homogeneity of variance were evaluated using the Shapiro–Wilk and Levene’s tests, respectively. Since both assumptions were not satisfied ($p < 0.05$), Welch’s t -test was applied at a significance level of $\alpha = 0.05$ [12,13].

Calorific Value Test

The calorific value of the solid propellant was determined using a bomb calorimeter (IKA C2000 series) under closed-combustion conditions. The samples were completely combusted in an oxygen atmosphere, and the calorific value was calculated based on the increase in the water temperature inside the calorimeter, in accordance with the ASTM D4809 standard.

Reaction Enthalpy Calculation

The reaction enthalpy calculation was used to estimate the combustion energy of magnesium–sodium nitrate-based propellants. The combustion reaction was assumed to follow an ideal stoichiometric reaction as follows:



The reaction enthalpy was calculated based on the standard enthalpies of formation (ΔH_f°) of each compound under standard conditions (25 °C and 1 atm), using Equation (3):

$$\Delta H_{\text{reaction}}^\circ = \sum v \Delta H_f^\circ \text{ products} - \sum v \Delta H_f^\circ \text{ reactants} \quad (3)$$

Where $\Delta H_{\text{reaction}}^\circ$ is the reaction enthalpy (kJ mol^{-1}), v represents the stoichiometric coefficient, and ΔH_f° denotes the standard enthalpy of formation. The standard enthalpy of formation data used in this study are summarized in Table 1.

Table 1. Standard Enthalpy of Formation Data

Compound	ΔH_f° (kJ mol^{-1})
$\text{Mg}_{(s)}$	0
$\text{NaNO}_{3(s)}$	-467
$\text{MgO}_{(s)}$	-601.6
$\text{Na}_2\text{O}_{(s)}$	-414
$\text{N}_{2(g)}$	0

Note: (s) = solid, (g) = gas.

The reaction enthalpy calculated using Hess's law was initially expressed in kJ per mole of reaction. To convert this value into a mass-based unit (cal g^{-1}), the following steps were applied. First, the reaction enthalpy in kJ mol^{-1} was converted to calories using the conversion factor $1 \text{ kJ} = 239.006 \text{ cal}$. Second, the total molar mass of the reactants corresponding to the stoichiometric reaction ($5\text{Mg} + 2\text{NaNO}_3$) was calculated (approximately 291.5 g mol^{-1}). Finally, the energy value in cal mol^{-1} was divided by the total molar mass of the reactants (g mol^{-1}), yielding the reaction enthalpy in cal g^{-1} . This procedure ensures transparency and reproducibility in the unit conversion.

Results and Discussion

Physical Appearance of the Propellant

Physically, the propellant samples were odorless and exhibited a hard texture. The samples were solid in form with relatively uniform dimensions, where the propellant containing activated carbon showed a darker color compared to the sample without activated carbon. Macroscopic observations indicated no significant differences in physical shape among the propellant variations, and the samples did not exhibit flammable or explosive behavior during handling under laboratory conditions in the absence of an ignition source.

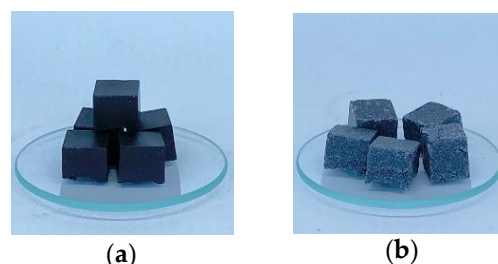


Figure 1. Visual appearance of the molded propellant samples: (a) Mg-NaNO_3 with activated carbon and (b) Mg-NaNO_3 without activated carbon.

Burning Rate of the Propellant

The burning rate test results of magnesium–nitrate-based propellants without and with activated carbon addition were obtained from five experimental replicates and are expressed as mean $\pm$ standard deviation. A comparison of the burning rate results is presented in Table 2.

Table 2. Burning rate of Mg-NaNO_3 propellants

Sample Composition	Burning Rate (cm s^{-1})
$\text{NaNO}_3/\text{Mg}/\text{AC}$	0.030 ± 0.001
NaNO_3/Mg	0.041 ± 0.001

Note : (mean $\pm$ SD, n = 5).

Based on Welch's t-test, a statistically significant difference in burning rate was observed between propellants without and with activated carbon addition ($t = -20.4$, $df = 5.88$, $p < 0.001$). The reporting of the burning rate in terms of mean and standard deviation was

employed because this parameter exhibits natural variability, making repeated measurements necessary to obtain a reliable representation of combustion characteristics [8]. The relatively small standard deviation indicates good repeatability of the measurements and reflects stable combustion behavior during the tests.

The decrease in burning rate observed in propellants containing activated carbon indicates the influence of carbon additives on the combustion mechanism. Carbon-based materials have been reported to modify combustion characteristics through changes in heat-transfer mechanisms and reaction kinetics during the combustion process. The presence of carbon particles can alter heat transport mechanisms, leading to a reduction in local temperature and slower propagation of the combustion front [14].

Similar phenomena have also been reported in various other solid propellant systems, where the addition of carbon-based materials has been associated with reduced heat feedback from the flame and disrupted diffusive interactions between reactants at the combustion surface [15]. This indicates that the role of carbon in propellant systems does not always involve accelerating combustion, but can instead function as a burning rate modifier depending on its properties and interaction mechanisms.

Based on the experimental results of this study, the addition of activated carbon to magnesium–sodium nitrate propellants was proven to significantly reduce the burning rate in a statistical sense. These findings confirm that the presence of carbon additives influences the combustion characteristics of the system.

Calorific Value of the Propellant

The calorific values of Mg–NaNO₃ propellants without and with activated carbon addition are presented in Table 3. The results indicate a difference in calorific value between the two propellant compositions, suggesting that the addition of activated carbon affects the energetic properties of the system. This difference reflects a change in the amount of thermal energy released during the combustion process.

Table 3. Calorific Value of Mg–NaNO₃ propellants

Sample Composition	Calorific Value (cal g ⁻¹)
NaNO ₃ /Mg/AC	2617
NaNO ₃ /Mg	2395

The increase in calorific value from 2395 cal g⁻¹ to 2617 cal g⁻¹ can be partly associated with the intrinsic calorific contribution of activated carbon. As a carbon-based material, activated carbon inherently contributes to the overall heat output of the formulation. The observed enhancement thus reflects both changes in combustion behavior and the compositional energy contribution of the additive. The reported calorific values are normalized to the total mass of the composite propellant, including Mg, NaNO₃, activated carbon, and binder.

In line with the obtained calorific value results, the energetic properties of the propellant were further analyzed through the calculation of the combustion reaction enthalpy of the Mg–NaNO₃ system. The calculation results indicate that the combustion process is exothermic, which is consistent with the nature of solid propellants as energetic materials. The reaction enthalpy value provides a theoretical description of the potential energy released during the combustion process.

Table 4. Combustion Reaction Enthalpy of Mg–NaNO₃ Propellants

Parameter	Value
ΔH (kJ mol ⁻¹)	-2488
Heat of combustion (cal g ⁻¹)	-2039
Reaction Characteristics	Exothermic

The theoretical approach to combustion energy in this study is based on the reaction enthalpy calculation method commonly applied in thermochemical analyses of energetic materials, namely through the application of

Hess's law using standard enthalpy of formation data for the reactants and products [16,17]. The combustion energy obtained from theoretical calculations represents the magnitude of the reaction energy based on the assumption of an ideal reaction and a predefined composition of combustion products.

In contrast, the calorific value obtained from bomb calorimeter testing reflects the thermal energy released during the actual combustion process. Differences between theoretical energy values and experimental results may arise due to variations in reaction assumptions, calculation methods, and measurement conditions. Furthermore, discrepancies in combustion energy values can be influenced by the definition of the system's final state and the thermodynamic approach employed in the analysis, such that the same combustion system may yield different energy values depending on the calculation method applied [18].

Accordingly, for the system with activated carbon addition (NaNO₃/Mg/AC), the determination of combustion energy was based on the calorific value obtained from bomb calorimeter testing, which represents the experimentally measured combustion energy under the specific testing conditions.

The theoretical stoichiometric proportions of the reaction (5Mg + 2NaNO₃) correspond to approximately 41.7% Mg and 58.3% NaNO₃ by mass. In comparison, the experimental formulations employed in this study were designed with different mass compositions (50:50 and 40:40:20), resulting in slightly fuel-rich mixtures relative to the stoichiometric condition. Such compositional differences may influence combustion efficiency and may partly account for the variation between the theoretically calculated enthalpy values and the experimentally measured calorific values.

Propellant Combustion Mechanism

Chemically, the combustion of Mg–NaNO₃ propellants proceeds through a series of reaction stages initiated by the thermal decomposition of sodium nitrate at high temperatures. At this stage, sodium nitrate decomposes and releases oxygen, which

subsequently acts as the oxidizer in the combustion system:



The oxygen released during the initial stage of combustion plays a role in initiating and sustaining the oxidation reaction of magnesium as the primary fuel. The oxidation of magnesium proceeds rapidly and is exothermic, thereby serving as the main source of combustion energy:



In addition to the formation of magnesium oxide (MgO) as the primary product, subsequent reactions between magnesium and nitrate decomposition products can produce sodium oxide (Na₂O) and nitrogen (N₂). Overall, the combustion mechanism of the Mg–NaNO₃ system can be expressed by the following ideal stoichiometric reaction:



This sequence of reactions indicates that the primary source of combustion energy originates from the oxidation of magnesium, while sodium nitrate functions as an oxygen supplier that supports the continuity of the combustion reaction.

In the system with activated carbon addition (NaNO₃/Mg/AC), the primary combustion reaction still proceeds through the Mg–NaNO₃ mechanism as previously described. The addition of carbon additives does not alter this primary reaction; however, it modifies the combustion mechanism through its involvement in secondary exothermic reactions resulting from interactions with nitrate decomposition products in the vicinity of the combustion zone, thereby providing localized heat contributions. This contribution is supportive in nature and does not replace the role of magnesium as the primary fuel governing oxide product formation.

In addition to these reaction contributions, the presence of carbon particles as inert additives also influences combustion through physical and thermal mechanisms.

Carbon particles can absorb and redistribute heat from the surrounding energetic material, thereby modifying the energy available to sustain combustion and potentially affecting the propagation of the combustion front.

The role of carbon as a regulator of thermal feedback is consistent with the modern understanding of the function of carbon materials in energetic material systems, which emphasizes their contribution to the physical and thermal aspects of the combustion process rather than their role as primary reactants. Previous studies have shown that the combustion process may be accompanied by the formation of a carbon layer on the reaction surface. The presence of a carbon layer with relatively high thermal conductivity contributes to enhanced heat transfer to the condensed phase [19].

The combustion mechanism proposed in this study should be understood as interpretative and based on the observed experimental trends together with comparison to relevant literature. Similar combustion-modifying effects of activated carbon in nitrate-based energetic systems have been reported, where activated carbon reduced decomposition temperature and activation energy due to its high surface area and catalytic interactions [20]. In addition, carbon-based additives have been shown to enhance heating value and propulsion performance in composite propellant systems [21]. These findings provide supporting context for the thermal feedback and combustion modification effects observed in the present Mg–NaNO₃ formulation.

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Conclusion

Magnesium–sodium nitrate (Mg–NaNO₃)–based solid propellants exhibit differences in combustion characteristics with the addition of

activated carbon. The addition of activated carbon significantly reduces the burning rate and increases the calorific value compared to propellants without activated carbon, indicating changes in the thermal and energetic characteristics of the system. Accordingly, activated carbon acts as an additive that modifies combustion behavior without altering the primary reaction of the Mg–NaNO₃ system.

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