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COB-2023-1982 THE EFFECTS OF CONTROLLED IRON OXIDE, ALUMINUM PARTICLES, AND CRIMSON POWDER ADDITION ON SOLID PROPELLANTS

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Abstract. *Research on combustion-enhancing additives plays a pivotal role in advancing solid propellant technology. This study focuses on the effects of these additives, specifically in the context of potassium nitrate and sorbitol-based propellants (KNSB). We examined the effects of incorporating three additives - iron oxide, aluminum particles, and Crimson Powder - at a 5% mass ratio. The propellants were manufactured using a standardized process to ensure reliability of results. Burn tests were conducted to measure regression rates and total impulse generated. Furthermore, differences in curing time of propellant grains and their moisture absorption were observed. Overall, the combination of KNSB with these additives exhibited superior performance compared to pure propellants, with the KNSB and Crimson Powder mixture standing out. These findings hold promise for the development of more efficient thrust-to-mass ratio propellant combinations. Research into combustion-enhancing additives in solid propellants is critical for advancing more efficient propulsion systems. Incorporating iron oxide, aluminum particles, and Crimson Powder into propellants, with an emphasis on KNSB propellant, yielded notable performance improvements and expands our knowledge in propellant technology, potentially leading to more effective propulsion systems in the future.*

Keywords: *Solid Propellants, Propulsion, Additives, Specific Impulse.*

1. INTRODUCTION

The growth of space exploration has been exponential in recent decades. This development has led to the emergence of rocketry as a hobby and research activity for many young individuals and science enthusiasts around the world. The increase in private investment in this field has further fueled the growth of such research. Currently, a significant portion of rockets and spacecraft in general employ liquid propulsion. However, there are still numerous agencies and companies that continue to work with solid propellants, either in hybrid spacecrafts or those entirely propelled by solid propellants. The principle of spacecraft propulsion is based on Newton's third law, as the gases expelled from the burning propellant propel the rocket. The concept of nozzles is also of paramount importance in this field, as they are designed to accelerate the combustion gases to increase the generated thrust (Sutton and Biblarz, 2001).

As technological advancements continue to push the boundaries of space exploration, there is a heightened focus on improving efficiency, safety, and sustainability in rocket launches. Innovations in propulsion systems, materials, and manufacturing techniques are pursued to optimize performance while minimizing expenses. Furthermore, collaborative efforts between government agencies, private enterprises, and research institutions aim to foster knowledge sharing and accelerate progress in this rapidly evolving field. The use of metallic additives as catalysts for the reaction in hybrid rocket propulsion engines has been examined (Izham and H. N Norhuda; Muhammad H. A., 2022). It has been demonstrated that the incorporation of these additives in paraffin-based grains results in enhancements in the regression rate, specific impulse, and combustion efficiency. This study involves the utilization of metals and metal hydrides.

The potential benefits of space exploration, such as advancements in communication, resource utilization, and scientific discoveries, further fuel the demand for continuous improvement in space-related endeavors. This growing awareness and recognition of the significance of the space science industry contribute to its perpetual development and increasing prominence on a global scale. In the realm of amateur and university-level rocketry, solid propellants commonly employed consist of potassium nitrate as the oxidizer and various types of sugars as the fuel. The prevailing combination entails potassium nitrate and sorbitol as the most widely used mixture. To enhance the propellant's overall impulse without significant mass alteration, the incorporation of additives becomes essential to augment its oxidation capabilities. The additives selected for this research endeavor comprise iron oxide, aluminum nanoparticles, and Crimson Powder. The choice of iron oxide and aluminum nanoparticles stems from their established use as additives in solid propellants, while Crimson Powder, known for its high burn rate, offers the potential for a substantial increase in total impulse generated. Iron oxide provides significant increase to the burning rate of composite solid propellants, as found by Budhwar *et al.* (2018) and Stephens *et al.* (2009). Moreover, increasing propellant chemical efficiency, that is, energy per unit mass, leads to a decrease in erosive burning (Ishihara and Kubota (1988)), which in turn increases total motor efficiency.

2. LITERATURE REVIEW

2.1 Specific Impulse

The main goal of this article is to research methods of enhancing propellant efficiency. Therefore, it is critical to define Specific Impulse, one of the most important parameters for measuring propellant performance. Bipropellant rockets carry both fuel and oxidizer used to generate thrust; the use of additives (serving as oxidizers) can increase the combustion's efficiency and increase the burn rate of the propellant, thus optimizing the propellant's Specific Impulse, defined by Sutton and Biblarz (2001) as:

$$I_S = \frac{I_t}{m_p \cdot g} \tag{1}$$

where I_S is the Specific Impulse, I_t is the Total Impulse, m_p is the total propellant (oxidizer + fuel) mass and g is the acceleration of gravity near the Earth's surface ($g \approx 9.8066$ m/s^2).

Near Earth's surface, Specific Impulse is equivalent to the ratio between the total impulse generated by the motor and the propellant weight it needs to carry to generate such impulse.

2.2 Burning Rate

The burning rate of a solid propellant is an important design factor, for it is related to the Specific Impulse of said propellant. According to Sutton and Biblarz (2001), the burning rate of a solid rocket propellant grain—that is, the rate at which a certain length of propellant turns to the gaseous state—is often related to the pressure at which the burn occurs, governed by the general equation:

$$r = aP^n \tag{2}$$

where r is the Burning Rate of the propellant, P is the Operating Pressure at which the burn occurs, and a and n are the Temperature Coefficient and the Burning Rate Exponent, respectively - both are constants that must be determined through experimentation for every propellant, and may assume different values at different pressure ranges.

Thus, the burn rate curve of the studied propellants is directly tied to the pressure. Furthermore, according to Sutton and Biblarz (2001), finer propellant particle sizes lead to higher burn rates. As noted by Shekhar (2015), a propellant with a higher burning rate exponent leads to peak-forming thrust curves, due to its connection to pressure and thrust generation, and lower n values lead to more stable, symmetrical pressure and thrust curves. The article by Babuk *et al.* (2005) corroborates this, stating that the use of additives can generate propellants of lower n values, higher burn rates and lower dependency of burn rate on pressure.

3. METHODS

3.1 Additives

The following additives' effects on propellant burn times, efficiency and general behavior were measured.

3.1.1 Aluminum

The aluminum particles had a size of 7-15 microns.

3.1.2 Iron Oxide

The red iron oxide was obtained through an electrolysis process. Afterward, it was dried for 2 hours inside an oven heated to 150 °C. Iron oxide particles have a size of 0.25-0.65 microns, according to Budhwar *et al.* (2018).

3.1.3 Crimson Powder

Crimson Powder is used for parachute ejection systems in rocketry. Its composition includes potassium nitrate, ascorbic acid, and red iron oxide.

3.2 Propellants

3.2.1 Chemical Evaluation of propellants

Initially, computational analyses were conducted using the ProPREP3 software to examine the properties of various propellant compositions and their additives. The additives constitute 4.76% of the total mass of the propellant mixture, which is 5% higher than the initial mass of pure propellant. The selected propellant was KNSB due to the existence of extensive research on its high efficiency, the safety provided by its high auto-ignition temperature of over 300 ºC, according to data retrieved by Nakka (2018), and the ease of manufacturing it provides.

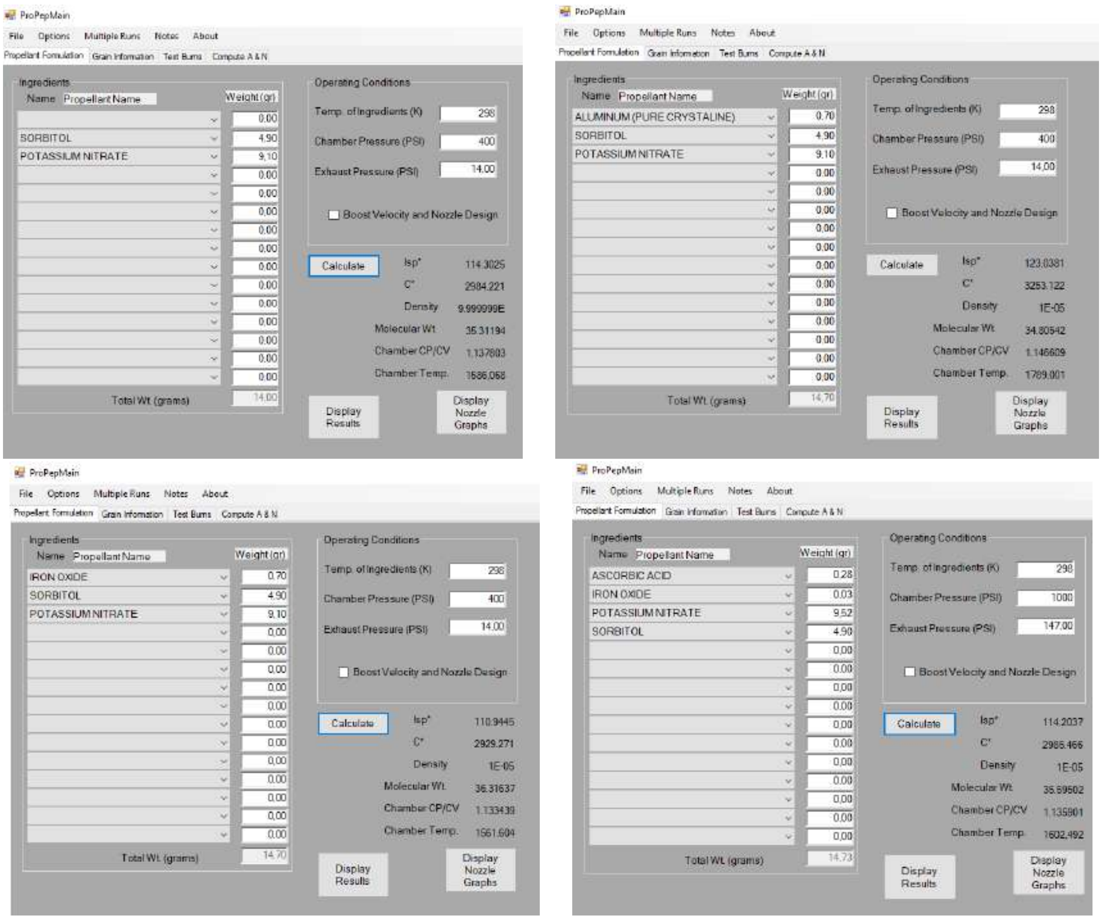


Figure 1. ProPep3 Simulations

The most important outputs provided by ProPep3 are $I_{SP}*$, c^* and Chamber Temperature. $I_{SP}*$ is the Specific Impulse ideal value corrected for a real nozzle's non-ideal efficiency in expanding the combustion gases and converting their heat and pressure into thrust. The term c^* is the characteristic velocity of the propellant, one of it's performance-measuring parameters. Finally, the predicted chamber temperature is the maximum chamber temperature that propellant mixture is expected to reach during combustion. The results for the selected combinations are shown in fig.8. Aluminum is the additive that most significantly changed the simulation results.

3.2.2 Manufacturing

Following the computational simulations, test specimens were fabricated for combustion testing, aiming to compare the burning times of different compositions. The components, including the additives, were thoroughly mixed and ground using a coffee grinder to ensure homogeneity, as shown in fig.2 . Subsequently, they were carefully cast, as seen in fig.3, with temperature controlled by a thermometer and placed into standardized copper molds measuring 50 mm in length and

14 mm in diameter.

Figure 2. KNSB Propellant with iron oxide addition, inside grinder.

Figure 3. Casting of propellants with the addition of aluminum and Crimson Powder, respectively.

The samples were stored using hermetic bags with calcium chloride to prevent them from absorbing moisture and experiencing poor performance during combustion.

The ignition of these test specimens was accomplished using standardized, centrally positioned igniters to ensure radial homogeneity of the burning. The burnings were recorded, and the data was analyzed subsequently.

Each test specimen was subjected to the same ignition method and burn conditions, ensuring consistency throughout the experiment. The first tests were conducted without a pressurized chamber. The recorded burnings were analyzed to extract valuable insights into the burning behavior and performance of the different propellant compositions. The collected data and analytical findings will serve as a foundation for further research and development in the field of propellant formulation, aiding in the design and optimization of propellants for various applications, including model rocketry and other propulsion systems.

Subsequently, samples were produced for the purpose of testing within a combustion chamber utilized as a propulsion system in rocket modeling practices. The motor incorporates an isolated chamber, where the sole outlet is a nozzle, serving to accelerate the gas resulting from combustion and ensuring chamber pressurization during propellant consumption.

The nozzle, shown in fig.4, features an internal throat diameter of 5 mm and convergence and divergence angles of 30° and 12°, respectively. The grains were standardized with internal diameter measurements of 8 mm, an external diameter of 19 mm, and a length of 45 mm. Each burning process was conducted with two grains, with only the inner surface remaining uninhibited for combustion, as in fig.5.

Figure 4. Steel DeLaval Nozzle

Figure 5. White - KNSB pure; Brown - Crimson Powder addition; Orange - Iron oxide addition; Gray - aluminum addition.

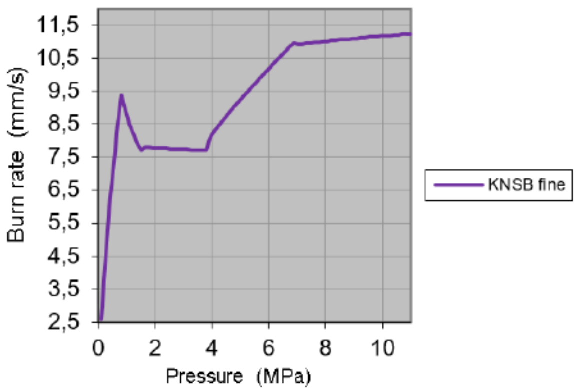
Subsequently, the samples were subjected to testing within a motor, employing a thrustometer equipped with a load cell, shown in fig. 6.

Figure 6. Thrustometer

3.3 Burn Rate

As initial approximations, assuming the burn that occurs in these cylinders has constant pressure and that the regression these grains present is linear, the burn rate can be estimated by dividing the length (mm) by the burn time (s).

Utilizing Eq. (2), the values of a and n can be determined for each of the propellant mixtures, as to provide initial data on their burn rate. Figure 7 shows data related to the burning rate of pure KNSB propellant in different motor operating pressure ranges, as experimentally determined by Nakka (2018), for reference.



(a)

KNSB Fine				
			a	n
Pressure, Mpa			Mpa, mm/sec	
0,101	to	0,807	10,708	0,625
0,807	to	1,503	8,763	-0,314
1,503	to	3,792	7,852	-0,013
3,792	to	7,033	3,907	0,535
7,033	to	10,67	9,653	0,064

(b)

Figure 7. (a) Burn Rate r as a function pressure P. (b) Values for a and n for different pressure ranges.

4. RESULTS

Initially, it was observed the difficulty in achieving complete curing of the samples with iron oxide additive, as rust is composed of iron hydroxide and hydrated iron oxides. The presence of water molecules significantly hinders the achievement of perfectly dry curing of the samples. Consequently, these samples remain pliable for a longer period, even when stored in a hermetically sealed container with calcium chloride to absorb moisture. The complete curing time for the pure KNSB, KNSB + aluminum, and KNSB + Crimson Powder samples was 2 days, whereas the KSNB + iron oxide samples required 7 days for complete curing.

Simultaneously, it was noteworthy the difference in thermal conductivity of the propellants with metallic additives. During the casting process, the propellants mixtures with metallic additives reached the melting temperature of sorbitol approximately 5 minutes earlier than the samples without metallic addition.

The burning tests resulted in different burning times, which corroborated the initial hypothesis that the additives would accelerate the combustion of the propellants. It is worth noting that the average KNSB + aluminum propellant's average burning time falls within the standard deviation for the pure KNSB burning time as illustrated in Table 1.

Table 1. Strand Burning Tests results at $P = 0.101$ MPa

Sample	Burning time [s]	Burn Rate [mm/s]
KNSB	19.03 ± 0.7	2.631 ± 0.097
KNSB + Iron Oxide	14.8 ± 0.5	3.382 ± 0.114
KNSB + aluminum	18.5 ± 1.3	2.716 ± 0.191
KNSB + Crimson Powder	9.01 ± 0.3	5.556 ± 0.185

According to experimental data by Nakka (2018), the burn rate for pure KNSB under the pressure of the standard atmosphere (0.101 MPa) can be calculated to be 2.555 mm/s. This result matches the interval estimated by the experimental data collected.

Three combustion tests were conducted using each type of sample with the pressurized chamber and the thrust meter. The results, shown in fig. 8 and Table 2 demonstrate the additives' ability to enhance the propellant's performance by enhancing the chamber pressure end Isp, this will be discussed in next sections. .

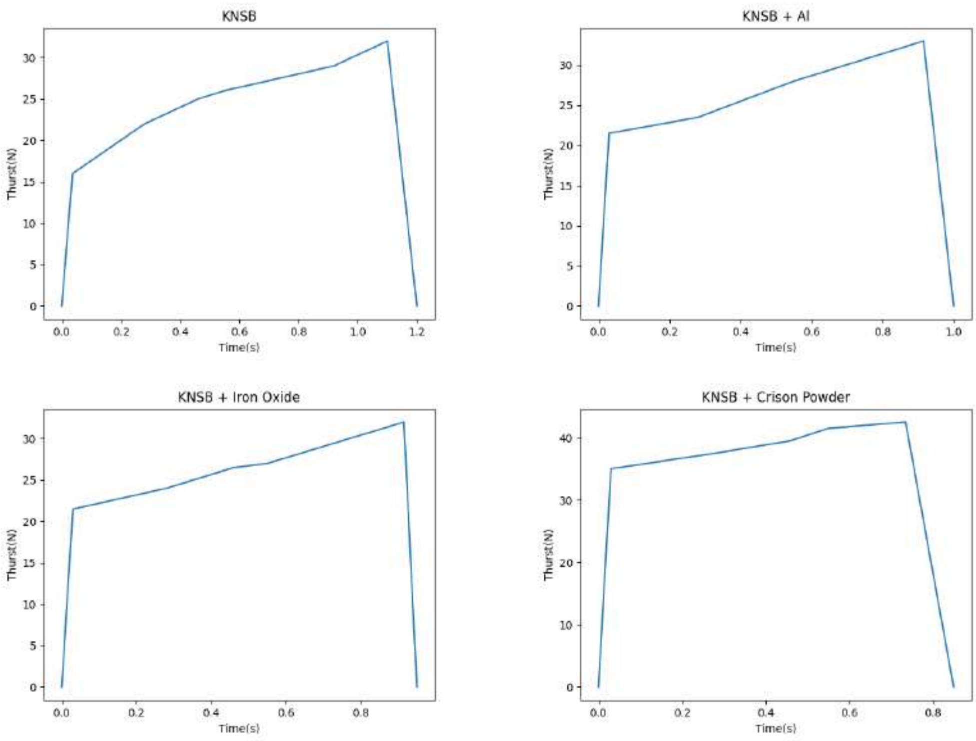


Figure 8. Thrust Curves

Table 2. Burning Tests

Sample	Burning time (s)	Maximum Thrust(N)	Total Impulse (Ns)	Specific Impulse (s)
KNSB	1.2 ± 0.1	32 ± 2	28.8 ± 1.5	75.23 ± 3.13
KNSB + aluminum	1.0 ± 0.1	33 ± 2	30.9 ± 1.3	80.72 ± 2.55
KNSB + Iron Oxide	0.95 ± 0.1	34 ± 2	32.8 ± 1.4	85.69 ± 2.76
KNSB + Crimson Powder	0.85 ± 0.1	42.5 ± 3	35.05 ± 2	91.55 ± 4.27

5. DISCUSSION

The additives have demonstrated the ability to increase the burning rate of the propellant at atmospheric pressure, as well as modify its casting and curing properties. It is expected that such additives are capable of delivering different pressures within a combustion chamber and enhancing the thrust generated with the same grain configuration and amount of propellant, given that the grain density does not change significantly, as the mass of the additives accounts for less than 5% of the total mass of the propellant. The manufacturing process undergoes minimal changes in the presence of additives, making the process highly viable.

The inclusion of all three additives led to an increase in both burn rate and specific impulse. The increase in specific impulse reached a maximum of 15.5% for the KNSB + aluminum, 22.7% for the KNSB + Iron Oxide, and 32.9% for the KNSB + Crimson Powder propellant.

6. CONCLUSION

The incorporation of additives into the propellant demonstrates the potential for augmenting thrust generation, elevating operating pressures within the propulsion system, and extending burn durations, all while maintaining relatively negligible alterations in propellant density.

These additive agents exert a mitigating influence on the propellants' burn durations, concurrent with an amplification of their maximum thrust output and a consequential enhancement of their specific impulse. Quantitative analysis reveals average increases in specific impulse of 7.3%, 13.9%, and 21.7%, corresponding to the utilization of aluminum, iron oxide, and crimson powder as additives, respectively.

It is imperative to recognize that a swifter burn rate may indeed yield a heightened specific impulse (Isp), albeit indirectly. It is well-established that Isp is a function of chamber pressure, with higher pressure levels resulting in commensurately increased Isp values. Within the framework of grain or nozzle geometries, an accelerated burn rate translates to elevated chamber pressure and thrust, hence engendering a superior Isp. Nevertheless, it is prudent to acknowledge that Isp measurements at standard pressure may exhibit variance. Therefore, it is advisable to employ ProPep as a reliable tool for comparative analysis of theoretical Isp values across diverse propellant combinations.

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