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Optimizing Nozzle Expansion Ratios with Energetic Additives for Enhanced Hybrid Rocket Motor Efficiency

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ABSTRACT

Hybrid rocket motors (HRMs) combine the advantages of liquid and solid rocket propulsion systems, offering operational simplicity, safety, and cost-effectiveness. However, a significant challenge in HRMs is the low regression rate of solid fuel, which limits their thrust and overall performance. Various methods, such as fuel grain geometry modification, the use of swirling oxidizers, and the incorporation of energetic additives, have been explored to address this. Energetic additives, including aluminum (Al), magnesium (Mg), and high-entropy alloys (HEAs), are particularly effective in enhancing regression rates while influencing other motor characteristics such as thrust and nozzle erosion. This study investigates the effects of different energetic additives and varying nozzle expansion ratios (ε = 10, 15, 20) on thrust, regression rate, Mach number, and nozzle throat erosion. Results reveal that incorporating HEA at 10% significantly enhances performance, achieving a thrust of 91.61 N at ε = 20, compared to the baseline value of 71.53 N at ε = 10. The Mach number also increases notably, with HEA 10% yielding 3.631 at ε = 20, compared to the baseline value of 3.017 at ε = 10. Similarly, the regression rate improves from 1.15 mm/s (baseline at ε = 10) to 1.42 mm/s with HEA 10% at ε = 20. Regarding erosion characteristics, throat area increase is minimized for HEA additives, with a maximum percentage increase of 10% at ε = 20 for HEA 10%. The findings highlight that energetic additive, especially HEAs, effectively mitigate nozzle erosion while significantly improving thrust and regression rates. This research underscores the importance of optimizing additive composition and nozzle expansion ratios to enhance HRM performance and durability, paving the way for more efficient hybrid propulsion systems.

1. Introduction

Hybrid rocket motors (HRMs) have been a subject of interest in the propulsion community for nearly a century due to their unique combination of features that bridge the gap between liquid and solid rocket propulsion. The first documented development of HRMs dates back to the 1930s when liquid oxidizers such as gaseous oxygen were paired with solid fuels like rubber or paraffin-based materials. Unlike purely solid or liquid systems, HRMs offer controllability similar to liquid propulsion

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while retaining the simplicity and cost-effectiveness of solid systems. Over time, researchers have explored advancements in hybrid technology, emphasizing its potential for safe and versatile applications, including suborbital launches and reusable spacecraft [1-5]. Despite these advances, HRMs still need to overcome specific challenges that hinder their widespread adoption in high-performance aerospace missions.

The advantages of hybrid rocket motors stem from their operational safety and flexibility [1,6-8]. Unlike solid rocket motors containing the oxidizer and fuel in a single, potentially hazardous composition, HRMs store the oxidizer and fuel separately [9-11]. This separation reduces the risk of accidental detonation and allows for real-time control of the thrust, enabling throttling and shutdown during operation. Furthermore, HRMs are cost-efficient, as they require simpler infrastructure and manufacturing processes compared to liquid rocket engines. Additionally, they are considered environmentally friendly, as hybrid combustion typically produces fewer toxic byproducts. However, the disadvantages must be noticed. One of the primary limitations is the inherently low regression rate of the solid fuel, which restricts the rate at which the propellant is consumed, subsequently limiting the thrust [4,5,12-14].

One of the persistent challenges in hybrid rocket motor design is ensuring structural integrity while optimizing performance. The nozzle is a critical area of concern, as it operates under extreme conditions, including high temperatures, intense mechanical loads, and exposure to corrosive combustion products. Nozzle erosion is a significant problem in hybrid propulsion systems and is influenced by factors such as combustion temperature, particle impact from energetic additives, and oxidizer flow dynamics. The erosion process gradually degrades the nozzle material, altering its geometry and adversely affecting the flow of exhaust gases. This, in turn, reduces the nozzle's ability to expand the gases efficiently, lowering thrust performance and potentially destabilizing the motor. Studies by Jiang *et al.,* [4]and Kamps *et al.,* [14] quantified the impacts of nozzle erosion, highlighting its role in reducing motor lifespan and increasing maintenance costs.

Researchers have explored several techniques to enhance the performance of hybrid rocket motors and mitigate challenges such as low regression rates. These include altering fuel grain geometry to increase the exposed surface area, swirling oxidizer flow to enhance combustion efficiency, and introducing energetic additives to the solid fuel. Energetic additives such as aluminum (Al), magnesium (Mg), and high-entropy alloys (HEAs) have gained attention for their ability to increase regression rates by releasing additional thermal energy during combustion. Recent studies demonstrated that HEAs, in particular, not only improve thrust performance but also provide enhanced erosion resistance due to their high thermal stability [6,7,15]. Similarly, researchers have analyzed the effects of magnesium-based additives, noting improvements in combustion efficiency and structural durability [16]. Adjusting the nozzle expansion ratio (ε) has also been identified as a critical factor in optimizing motor performance.

This paper investigates the effects of energetic additives and nozzle expansion ratios on hybrid rocket motor performance and nozzle erosion. By systematically analyzing the influence of additives such as Al, Mg, and HEAs at varying expansion ratios, the study aims to provide valuable insights into improving thrust, regression rates, and nozzle erosion resistance. The findings contribute to developing more efficient and durable hybrid propulsion systems, offering solutions to longstanding challenges in the field.

2. Methodology
2.1 Theory and Chemical Reactions for Nozzle Erosion

In hybrid rocket motors (HRMs) with oxygen as the oxidizer, nozzle erosion emerges as a significant challenge due to the intense thermal and chemical environment created during combustion. The high-temperature exhaust gases contain oxygen, which reacts aggressively with the nozzle material, mainly graphite, causing its oxidation and subsequent degradation. The extreme conditions at the nozzle throat and exit lead to both chemical erosion and mechanical wear, compromising the nozzle's structural integrity and altering its geometry. These changes reduce the efficiency of gas expansion, ultimately degrading the motor's overall performance.

Oxidation reactions primarily drive the erosion process. Oxygen reacts with graphite to form carbon monoxide, (CO) and carbon dioxide (CO_2), With the reaction rate increasing with temperature. Additionally, the introduction of energetic additives, often used to enhance regression rates and motor performance, contributes to erosion. These additives produce solid oxides, such as aluminum oxide, (Al_2O_3) and magnesium oxide (MgO), which act as abrasive particles within the exhaust. Furthermore, water vapor, a byproduct of combustion, reacts with graphite to produce carbon monoxide and hydrogen, further intensifying material loss. These combined chemical and mechanical processes highlight the complex and multifaceted nature of nozzle erosion in hybrid rocket motors.

2.1.1 Oxidation of graphite:

Graphite nozzles are susceptible to oxidation in the presence of oxygen. The intense heat of combustion promotes rapid chemical reactions:

i) In an oxygen-rich environment, graphite is oxidized to form carbon dioxide (CO_2):
$$\mathrm{C} + \mathrm{O_2} \rightarrow \mathrm{CO_2} \tag{1}$$

ii) In areas of limited oxygen availability, carbon monoxide (CO) is the primary product:
$$\mathrm{C} + \frac{1}{2}\mathrm{O_2} \rightarrow \mathrm{CO} \tag{2}$$

The oxidation process depletes the nozzle material, leading to structural weakening and dimensional changes that reduce nozzle efficiency.

2.1.2 Reactions with energetic additives:

When energetic additives such as aluminum or magnesium are included to enhance the combustion process, additional reactions occur. These additives form solid oxides that are expelled at high velocity and contribute to erosion.

i) Aluminum reacts with oxygen to form aluminum oxide (Al_2O_3):
$$4\mathrm{Al} + 3\mathrm{O_2} \rightarrow 2\mathrm{Al_2O_3} \tag{3}$$

ii) Magnesium reacts similarly to form magnesium oxide (MgO):
$$2\mathrm{Mg} + \mathrm{O_2} \rightarrow 2\mathrm{MgO} \tag{4}$$

iii) The composition of the High-Entropy Alloy (HEA) used in this study consists of a combination of six primary elements: iron (Fe), nickel (Ni), cobalt (Co), silicon (Si), aluminum (Al), and boron (B), which collectively contribute to its unique properties of high-temperature stability, oxidation resistance, and mechanical strength.

$$4\mathrm{Fe}+3O_2 \rightarrow 2Fe_2O_3 \tag{5}$$

$$2\mathrm{Fe}+\mathrm{O}_2 \rightarrow 2\mathrm{FeO} \tag{6}$$

$$2\mathrm{Ni}+\mathrm{O}_2 \rightarrow 2\mathrm{NiO} \tag{7}$$

$$2\mathrm{Co}+\mathrm{O}_2 \rightarrow 2\mathrm{CoO} \tag{8}$$

$$\mathrm{Si}+\mathrm{O}_2 \rightarrow \mathrm{SiO2} \tag{9}$$

$$4\mathrm{Al} + 3\mathrm{O}_2 \rightarrow 2\mathrm{Al}_2\mathrm{O}_3 \tag{10}$$

$$4\mathrm{B}+3\mathrm{O}_2 \rightarrow 2\mathrm{B}_2\mathrm{O}_3 \tag{11}$$

2.2 Equations for Calculating Performance

The performance of a hybrid rocket motor can be evaluated using several key equations that relate to thrust, specific impulse, exhaust velocity, and other parameters. These equations are critical for quantifying the impact of nozzle erosion and optimizing motor efficiency.

$$V_{\mathrm{exit}} = \sqrt{\frac{2\gamma R T_c}{(\gamma - I)}\left\{1 - \left(\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right\}} \tag{12}$$

$$\dot{m}_{prop} = \frac{m_{after} - m_{before}}{t_b} \tag{13}$$

$$F = \dot{m}_{\mathrm{prop}} V_{\mathrm{exit}} + (\rho_{\mathrm{exit}} - \rho_{\mathrm{atm}})A \tag{14}$$

$$I_{\mathrm{sp}} = \frac{F}{\dot{m}_{ox} g_o} \tag{15}$$

$$G_0 = \frac{\dot{m}_o}{N A_p} \tag{16}$$

$$\dot{r} = \frac{r_{\mathrm{after}} - r_{\mathrm{before}}}{t_b} \tag{17}$$

2.3 Experimental Setup
2.3.1 HRM test bed

The hybrid rocket motor setup is equipped with a range of sensors to accurately measure critical parameters during the test as in Figure 1. A thermocouple is installed in both the pre-chamber and post-chamber of the rocket motor to monitor temperature variations. This strategic placement ensures that the thermal conditions of both the combustion process and exhaust stages are closely monitored, providing valuable data on the motor's thermal performance. In addition to the thermocouple, a pressure transmitter is also integrated into both the pre-chamber and post-chamber. These transmitters allow for continuous pressure measurements at key points within the rocket motor, enabling real-time monitoring of pressure fluctuations that can impact performance. The data obtained from these sensors is critical for understanding the combustion dynamics and ensuring safe operating conditions throughout the test.

A load cell is attached to the rocket motor assembly to measure the thrust generated during the firing. This sensor provides real-time thrust data, allowing for an assessment of the motor's performance and efficiency. All sensors, including the thermocouple, pressure transmitters, and load cell, are connected to a Data Acquisition System (DAQ), which records and transmits the data for analysis, as in Figure 2. The DAQ ensures that all measurements are captured and synchronized, providing a comprehensive dataset for post-test evaluation.

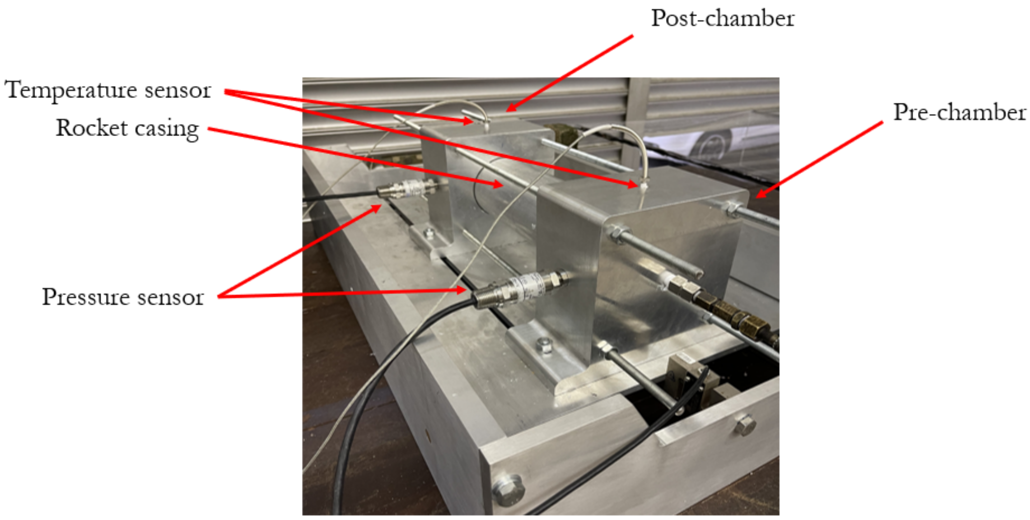

Fig. 1. Experiment set-up

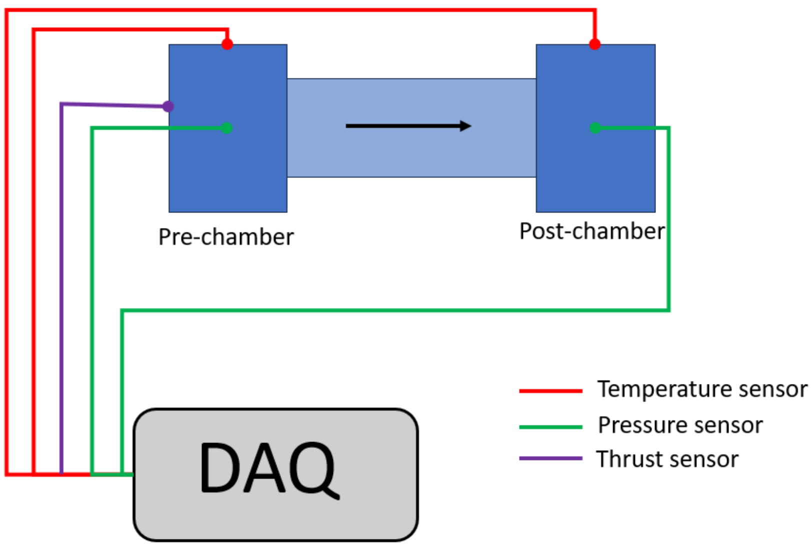

Fig. 2. Schematic diagram of Hybrid rocket motor (HRM)

Hybrid rocket motors use oxygen gas as oxidizers because they enable higher combustion temperatures, resulting in more excellent energy release and a higher specific impulse, which improves the rocket's overall performance. It simplifies the combustion process, as GOX directly reacts with the fuel, unlike N2O, which requires decomposition into nitrogen and oxygen before combustion. Additionally, GOX provides precise control of the oxidizer flow rate, allowing better optimization of the oxidizer-to-fuel ratio. Figure 3 and Figure 4 illustrate the oxygen gas tank and pressure regulator.

Fig. 3. Oxygen gas tank connected to the HRM

Fig. 4. Pressure regulator

2.3.2 HRM fuel classification

In this study, a hybrid rocket motor was tested with three different types of energetic additives: aluminum, magnesium, and a high-entropy alloy (Figure 5). These additives were selected for their potential to enhance combustion performance and influence the overall efficiency of the motor. The performance of each fuel type was systematically analyzed, with particular attention to key metrics such as thrust, specific impulse, and combustion efficiency. Additionally, the erosion rates of the nozzle material were closely monitored to assess the durability and sustainability of the system under operational conditions. To further investigate the impact of nozzle design on the motor's performance, each fuel was tested across three distinct expansion ratios (Figure 6), providing insights into the interplay between nozzle geometry and additive behavior.

Fig. 5. Three different types of additive with baseline

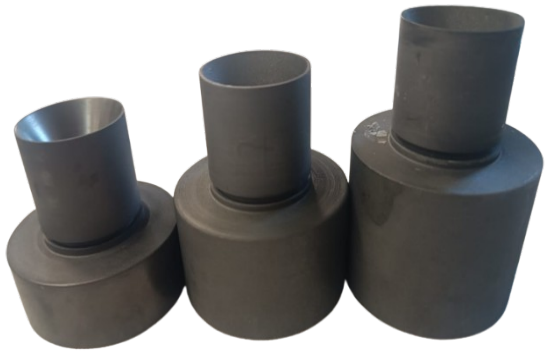

Fig. 6. Three different nozzles (ε=10; ε=15; ε=20)

Table 1 and Table 2 provide a comprehensive summary of the testing conditions and parameters established for the hybrid rocket motor (HRM) experiments. These experiments were designed to investigate the effects of varying expansion ratios and different types of energetic additives on the performance of the hybrid rocket motor, as well as the erosion rates observed at the nozzle.

Table 1
Experiment HRM testing

Testing	Sample	Additives percentage	Expansion ratio
1 (Baseline)	Paraffin Wax	5%	10
2	Paraffin Wax + Al	5%	10
3	Paraffin Wax + Al	5%	15
4	Paraffin Wax + Al	5%	20
5	Paraffin Wax + Mg	5%	10
6	Paraffin Wax + Mg	5%	15
7	Paraffin Wax + Mg	5%	20
8	Paraffin Wax + HEA	5%	10
9	Paraffin Wax + HEA	5%	15
10	Paraffin Wax + HEA	5%	20

Table 2
Parameter and fuel specification

	Fuel
Outer Diameter (mm)	41
Inner Diameter (mm)	20
Length (mm)	160
Oxidizer Inlet (kPa)	300
Burning time (s)	10

3. Result and Discussion

In this section, Table 3 presents the results obtained from the hybrid rocket motor (HRM) firing tests. Key parameters recorded during these tests include the initial and final fuel mass, pre-chamber and post-chamber pressures, pre-chamber and post-chamber temperatures, and the thrust generated.

Table 3
Fuel mass before and after testing

Testing	Sample	Mass initial (g)	Mass Final (g)
1 (Baseline)	Paraffin Wax	184	113.4
2	Paraffin Wax + Al	194	102.7
3	Paraffin Wax + Al	189	97
4	Paraffin Wax + Al	201	91
5	Paraffin Wax + Mg	186	109
6	Paraffin Wax + Mg	194	97
7	Paraffin Wax + Mg	193	89
8	Paraffin Wax + HEA	192	111
9	Paraffin Wax + HEA	201	96
10	Paraffin Wax + HEA	196	79

3.1 Performance of HRM

Figure 7 shows thrust (in Newtons), while Figure 8 represents the Mach number at the nozzle exit for the same conditions, which include the baseline and three additives: aluminum (Al), magnesium (Mg), and high-entropy alloy (HEA), tested at expansion ratios of ε = 10, 15, and 20. As the expansion ratio increases from ε = 10 to ε = 20, both thrust and Mach numbers improve for all fuel additives. This is expected because a higher expansion ratio allows for better conversion of thermal energy into kinetic energy, leading to higher exhaust velocities (indicated by higher Mach numbers) and greater thrust. Aluminum consistently produces the highest thrust and Mach number, suggesting that its high energy density and efficient combustion contribute to superior performance. HEA shows moderate thrust and Mach numbers, reflecting its lower energy density but lightweight nature, which supports nozzle flow acceleration. Mg, while still performing better than the baseline, delivers the lowest thrust and Mach number among the additives, suggesting that its combustion may not be as efficient in terms of energy release compared to aluminum and HEA.

Both graphs also highlight the improvement in performance with increasing expansion ratios. At ε = 20, the highest values for thrust and Mach number are achieved across all additives, demonstrating the importance of nozzle geometry in optimizing both thrust generation and exhaust flow velocity. The baseline, without any additives, shows the lowest thrust and Mach number in both graphs, reinforcing the critical role of energetic additives in enhancing the performance of the HRM.

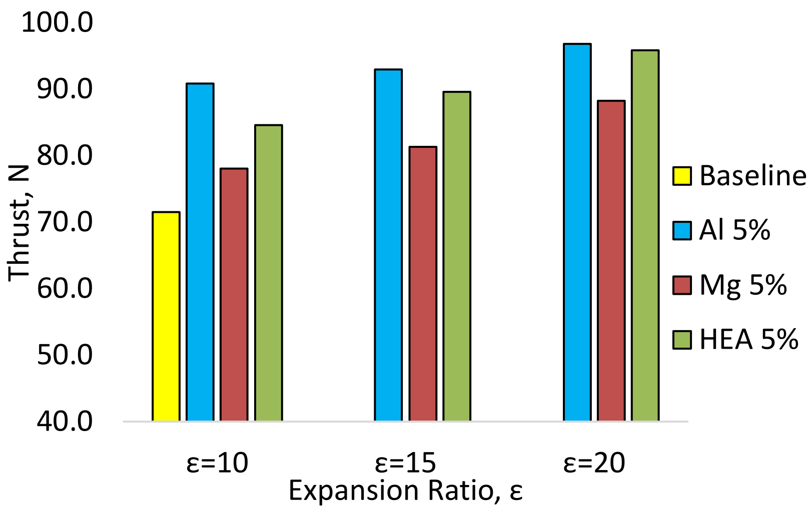

Fig. 7. HRM thrust performance

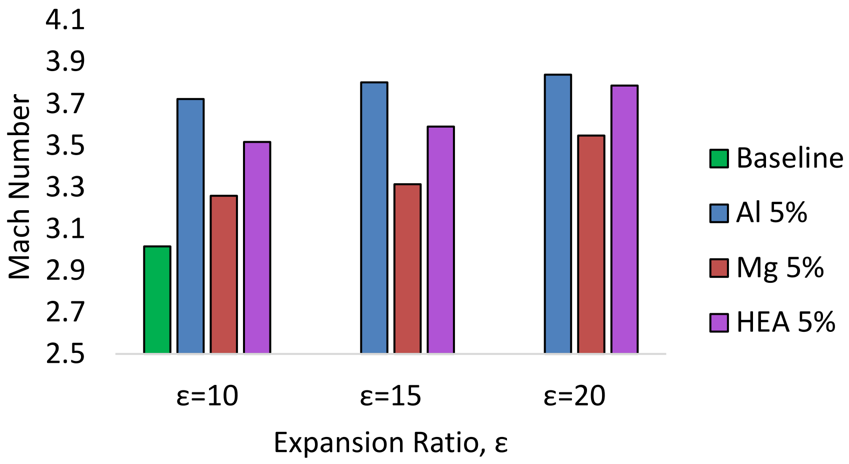

Fig. 8. HRM Mach Number

Figure 9 illustrates the regression rates of aluminum (Al), magnesium (Mg), and high entropy alloys (HEA) as propellant materials in combustion applications, with a focus on the effects of varying expansion ratios. Aluminum demonstrates a relatively modest change in regression rate when the expansion ratio is increased from 10 to 15, indicating a stable combustion efficiency within this range. However, when the expansion ratio is further increased to 20, aluminum exhibits a notable rise in its regression rate. This suggests that its combustion efficiency becomes significantly enhanced at higher expansion ratios due to increased flow dynamics or thermal effects. In the case of magnesium and HEA, the regression rates are initially similar at an expansion ratio of 10, implying comparable combustion behaviors under these conditions. As the expansion ratio increases, the regression rate of magnesium experiences a moderate rise, maintaining steady but less pronounced improvements in combustion efficiency. Conversely, HEA exhibits a significant increase in regression rate as the expansion ratio rises, showcasing a more pronounced enhancement in combustion efficiency. At the highest expansion ratio of 20, HEA achieves the highest regression rate among the three materials, surpassing both aluminum and magnesium. The superior regression rate of HEA at higher expansion ratios can be attributed to its complex multi-element composition, which likely facilitates better thermal stability and more efficient energy release during combustion. This behavior indicates that HEA has significant potential as a high-performance additive in combustion systems, particularly under conditions requiring high expansion ratios, where enhanced energy output and efficiency are critical.

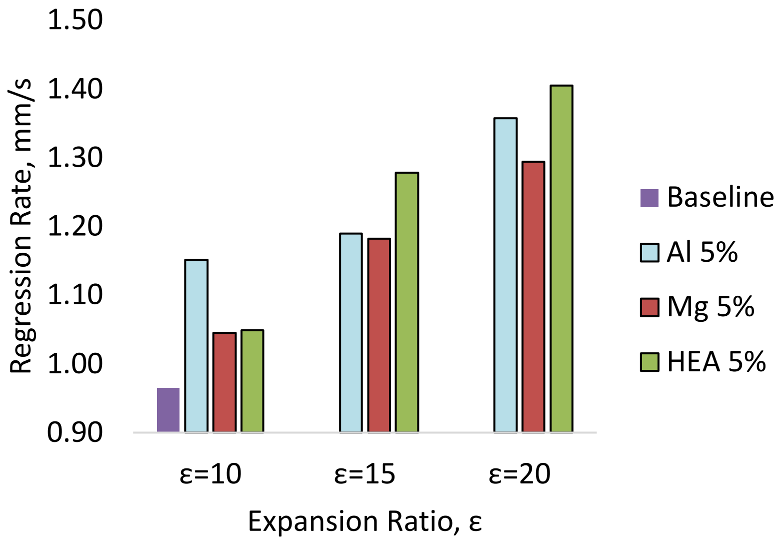

Fig. 9. Regression rate against expansion ratio

Figure 10 depicts the increase in nozzle throat diameter following the firing process. The results indicate that magnesium has a more pronounced effect on the nozzle throat expansion compared to the other additives, suggesting a higher level of erosion or material loss. In contrast, high entropy alloys (HEA) exhibit a relatively minor increase in the nozzle throat diameter, indicating that HEA causes less erosion during the combustion process. Figure 11 and 12 indicate the throat change of magnesium (highest) and baseline.

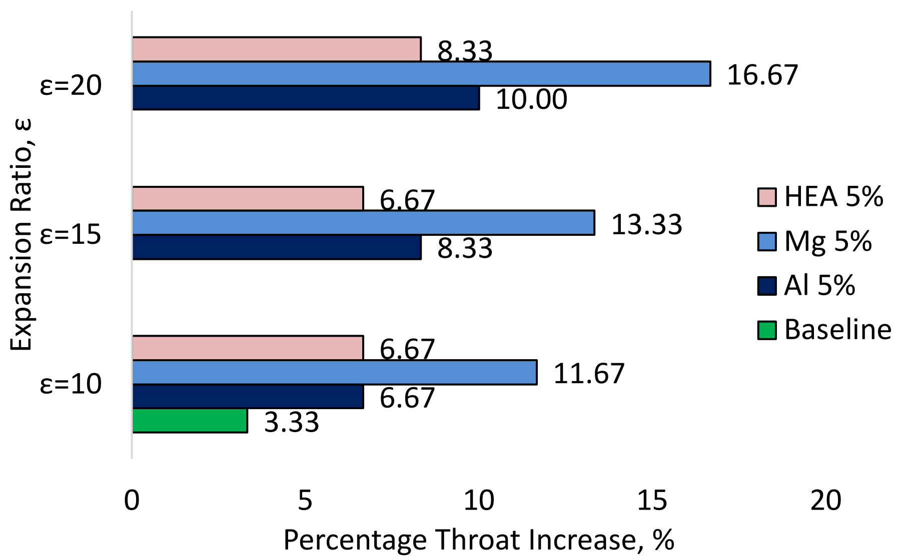

Fig. 10. Regression rate against expansion ratio

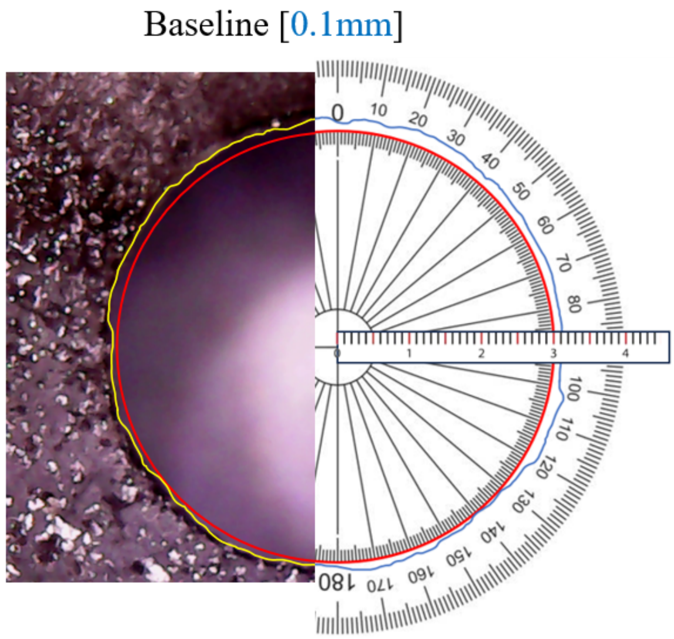

Fig. 11. Baseline

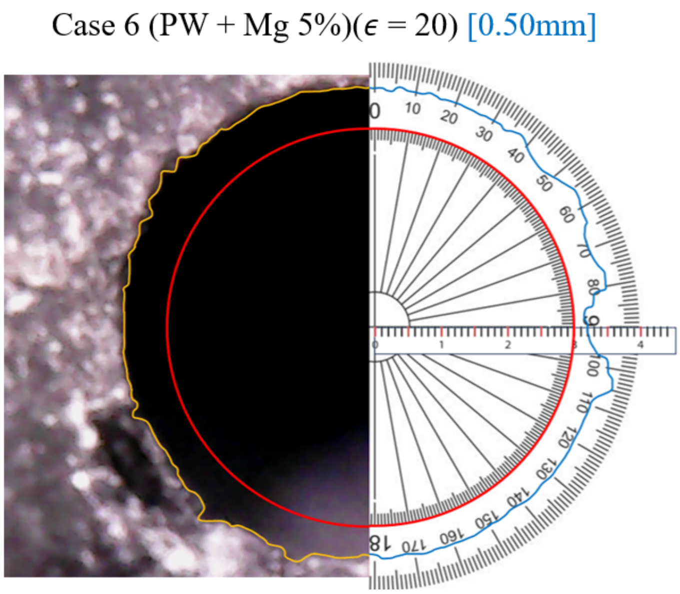

Fig. 12. Magnesium

4. Conclusions

In conclusion, this study explores several techniques for enhancing the regression rate of hybrid rocket motor (HRM) fuels, with a specific focus on the effects of varying expansion ratios and the incorporation of different additives. The primary objective was to evaluate their influence on both HRM performance and nozzle throat erosion. Among the additives investigated, high entropy alloys (HEA) emerged as a promising candidate with substantial potential for use as energetic additives. Although HEA exhibited a lower regression rate compared to aluminum, it outperformed magnesium in terms of both combustion efficiency and overall performance. Furthermore, HEA demonstrated relatively minimal nozzle throat erosion, suggesting its advantage in preserving nozzle integrity during combustion. The study also revealed that increasing the expansion ratio positively impacted the performance of all the tested fuels, resulting in higher regression rates and enhanced combustion characteristics. The inclusion of energetic additives, particularly HEA, was found to significantly improve the overall fuel performance, contributing to increased regression rates and more efficient combustion. These results highlight the effectiveness of both expansion ratio optimization and the use of high-performing additives in enhancing HRM fuel performance while minimizing adverse effects such as erosion. Overall, the findings underscore the potential of HEA as a viable and efficient additive for advancing HRM technology, offering a balance between improved combustion and reduced material degradation.

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