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Investigation of Regression Rate Enhancement of HTPB/Paraffin Fuel in the Hybrid Rocket Motor Utilizing High Entropy Alloys Energetic Additives

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ABSTRACT

Hybrid rocket motors are being looked at by the aerospace industry as an alternative to solid and liquid rocket power systems that is safer to use, move and handle. HRM still has several weaknesses that need to be explored such as low regression rate, poor combustion efficiency and also the ability to operate in large sizes. This research aims to conduct performance analytical and experimental comparison of HTPB/Paraffin fuel doped with HEA energetic additives for thrust, specific impulse and regression rates. The research analysed the Hybrid Rocker Motor's performance using ProPeP to determine the specific impulse and characteristic velocity of various propellant mixtures for comparison. Twenty-one HTPB/Paraffin fuel samples, with varying concentrations of energetic additives HEA and Ammonium Perchlorate, were fired on a lab-scale static bench equipped with a feeding system, combustion chamber, nozzle and data acquisition system for measurement and analysis. Analysed the results and determine the regression rate improvement of HTPB/Paraffin fuel with HEA additives and the correlation between regression rate and oxidizer mass flux. The experiment's findings indicated that adding HEA, Ammonium Perchlorate and Aluminium increased the regression rate. HEA demonstrates a 79% improvement, markedly lower than the 128% boost found with AP. Nonetheless, HEA enhances the thermal stability of the fuel mixture. ensuring uniform performance across different oxidizing conditions, as demonstrated in the hybrid formulation containing ammonium perchlorate (AP) and HEA. The integration of AP and HEA enhances heat distribution, hence promoting combustion stability.

1. Introduction

Hybrid rocket propulsion systems represent a compelling alternative to conventional solid and liquid rocket engines, offering a balance between safety, cost-effectiveness and performance [1]. Unlike solid rockets, which contain both oxidizer and fuel in a single propellant grain and liquid

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rockets, which require complex fuel-oxidizer injection and mixing mechanisms, hybrid rocket motors (HRMs) leverage a combination of a solid fuel and a liquid or gaseous oxidizer [2,3]. This configuration allows for operational flexibility, enhanced safety and controlled combustion, making hybrid propulsion an attractive option for various aerospace applications, including academic research, commercial space ventures and military applications [3-6].

HRMs exhibit several key advantages over traditional propulsion methods. The design significantly reduces the risks associated with propellant handling and storage since the fuel remains inert under standard conditions. Additionally, hybrid engines enable throttle control and shutdown capabilities, making them more adaptable compared to solid rockets [7-10]. The ability to select from various fuel and oxidizer combinations further enhances performance optimization for specific mission requirements [11].

Despite these benefits, hybrid rocket motors face challenges, particularly in achieving high regression rates of the solid fuel, optimizing combustion efficiency and mitigating performance losses due to oxidizer-to-fuel ratio variations. Research efforts have focused on improving these aspects by exploring different oxidizers such as hydrogen peroxide (H_2O_2), nitrous oxide (N_2O) and gaseous oxygen (GOx), as well as solid fuels like paraffin, hydroxyl-terminated polybutadiene (HTPB) and various energetic additives. These innovations aim to enhance combustion stability, increase regression rates and improve overall thrust performance [12].

Several studies have been conducted to improve the efficiency and performance of hybrid rocket motors, particularly by selecting fuels and oxidizers. Previous research has extensively explored using HTPB as a fuel due to its stability, energy density and mechanical integrity. HTPB-based fuels have been widely utilized in hybrid propulsion systems because they exhibit good structural properties, ensuring minimal fuel grain erosion and a steady burn rate [12]. Studies have demonstrated that blending HTPB with other materials, such as paraffin or aluminium powder, enhances fuel regression rates and improves combustion efficiency. Research has shown that incorporating aluminium into HTPB fuel can increase regression rates by as much as 88.8% [13].

Furthermore, recent advancements in hybrid propulsion research have focused on integrating high entropy alloys (HEAs) into HTPB/paraffin-based fuels to enhance combustion efficiency and thrust performance [14]. HEAs, due to their unique thermophysical properties, have demonstrated potential in accelerating fuel regression rates and improving energy release [15,16]. Studies have reported that HEA additives in hybrid rocket motors could increase regression rates by up to 93.5% compared to conventional fuels [14]. Additionally, advanced manufacturing techniques, such as additive manufacturing, have been explored to optimize fuel structure and combustion efficiency [17].

Other studies have also investigated the role of metals and alloys as energetic additives in hybrid rocket propulsion [18]. Aluminium has been found to improve the combustion efficiency of hybrid fuels, with recent work highlighting its ability to enhance regression rates and specific impulse when used in optimal concentrations [19]. However, challenges related to particle agglomeration, nozzle erosion and efficiency losses due to incomplete combustion remain areas of active research [20].

This study aims to analyse the performance of HTPB/Paraffin fuel doped with HEA energetic additives in hybrid rocket motors by evaluating its impact on thrust, specific impulse and regression rates through analytical studies. Additionally, the research involves developing and fabricating hybrid rocket motors using HTPB/Paraffin fuel doped with HEA additives at varying mass concentrations. To validate the findings, static firing tests will be conducted under different initial conditions to assess the influence of HEA additives on regression rate, thrust and specific impulse. Through this investigation, the study seeks to contribute to the optimization of hybrid propulsion systems by enhancing fuel efficiency, improving combustion characteristics and increasing thrust performance for future aerospace applications

2. Methodology

The study examined the addition of High Entropy Alloy (HEA) to hybrid rocket motors using fuel mixtures of paraffin wax and Hydroxyl-Terminated Polybutadiene (HTPB) by comparing various combustion scenarios.

2.1 Analytical Design Mathematical Setting

Consider the geometry of a cylindrical fuel port, see Figure 1 and the fuel dimension as in Table 1. The initial geometry is given through inner and outer diameters, d_i and d_o and length L.

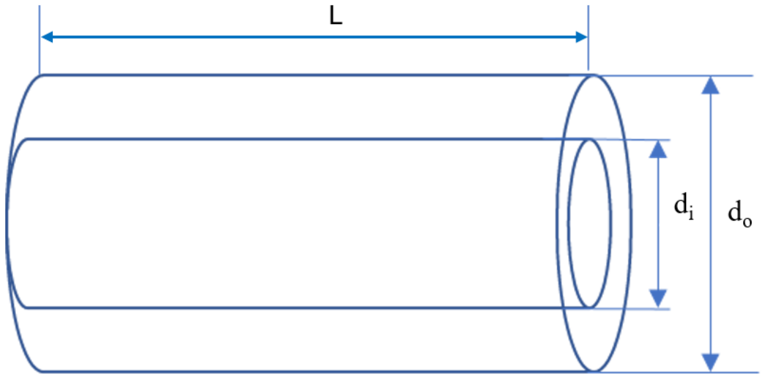


Fig. 1. Analytical fuel design

Table 1
Fuel dimension

Material	Fuel Composition Sample Test
Length (mm)	116
Outer Diameter (mm)	45
Inner Diameter (mm)	20

The main basic mathematical relationship between the real time regression rate, the real-time inner diameter (position of the combustion interface between flue gases and solid fuel) and the time is:

$$\partial(d) = 2 \cdot \dot{r}\partial t \quad (1)$$

Where, d is the inner diameter during combustion, $\dot{r}$ is the regression rate and t is time:

$$\dot{r} = a.(Gox)^n = a.\left(\frac{4.\dot{m}_o}{\pi.d^2}\right)^n = a.\left(\frac{4.\left(\frac{O}{F}\right).\dot{m}_f}{\pi.d^2}\right)^n = a.\left(\frac{4.\left(\frac{O}{F}\right).L.\rho.\dot{r}}{d}\right)^n \quad (2)$$

Where, Gox (gaseous oxygen) is the real time oxygen mass flux (kg/m2s), $\dot{m}_o$ (kg/s) is the real time oxygen mass rate, $\dot{m}_f$ (kg/s) is the real time mass rate of the fuel, d is the real time inner diameter (m), L (m) is the length of the fuel port, ρ is the fuel density (kg/m^3), O/F is the real time ratio of mass rates of oxygen and fuel, a and n have values experimentally obtained and supposed constant at any time of combustion. The Eq. (1) and Eq. (2) should be correlated by imposing initial design constraints and adopting input values of initial combustion system parameters.

2.2 Analytical Internal Ballistic Model

To investigate the effects of adding HEA to fuel, the study begins with an analytical evaluation of the performance parameters of HTPB and paraffin when combined with HEA. According to George P. Sutton (2010), the first step in designing a hybrid rocket motor is to specify the desired thrust (F) and select an appropriate propellant mixture. Once these parameters are defined, the characteristic velocity (c*) of the propellant is determined by choosing the optimal oxidizer-to-fuel ratio (O/F ratio). Key properties such as molecular mass, specific heat ratio and flame temperature can be obtained. These values are then used to calculate the characteristic velocity (c*) and nozzle exit Mach number using Eq. (3) and Eq. (4).

$$C^* = \frac{\eta_c * \sqrt{\gamma R T_f}}{\gamma \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2\gamma-2}}} \tag{3}$$

$$\varepsilon = \frac{1}{M_e}\sqrt{\left\{\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M_e^2\right)\right\}^{\frac{\gamma+1}{\gamma-1}}} \tag{4}$$

Using isentropic relation, the exit pressure can be calculated. Meanwhile, specific impulse is calculated from Eq. (5).

$$I_{sp} = \lambda\left\{\frac{C^*\gamma}{g_o}\sqrt{\left(\frac{2}{\gamma-1}\right)\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}[1-\left(\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}} + \frac{C^*\varepsilon}{g_{oP_c}}(P_e - P_a)\right\} \tag{5}$$

$$\dot{r} = a(G_{ox} + G_{fuel})^n L_p^m \tag{6}$$

$$V_e = \sqrt{\frac{2\gamma R T_o}{(\gamma-1)}\left\{1-\left(\frac{P_e}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right\}} \tag{7}$$

$$F = \lambda\left[\dot{m}_{prop}V_e + (P_e - P_a)A_e\right] \tag{8}$$

The total propellant flow rate and subsequent divide between oxidizer and fuel flow rates required to reach the required thrust level can be computed after the characteristic velocity and mixture ratio have been determined. Eq. (9) provides the entire starting propellant flow rate (ṁ), which is known.

$$\dot{\mathrm{m}} = \frac{g_o p_1 A_t}{c^*} \tag{9}$$

For mixture ratio (r), it defined as in Eq. (10) where $\dot{m}_o$ is Oxidizer mass flow rate and $\dot{m}_f$ is fuel mass flow rate;

$$r = \dot{\mathrm{m}}_O/\dot{\mathrm{m}}_f \tag{10}$$

The oxidizer mass velocity, also called the oxidizer flux, is primarily responsible for fuel regression rates. It is calculated by dividing the mass flow rate of the oxidizer in a combustion port by the cross-sectional area of the port.

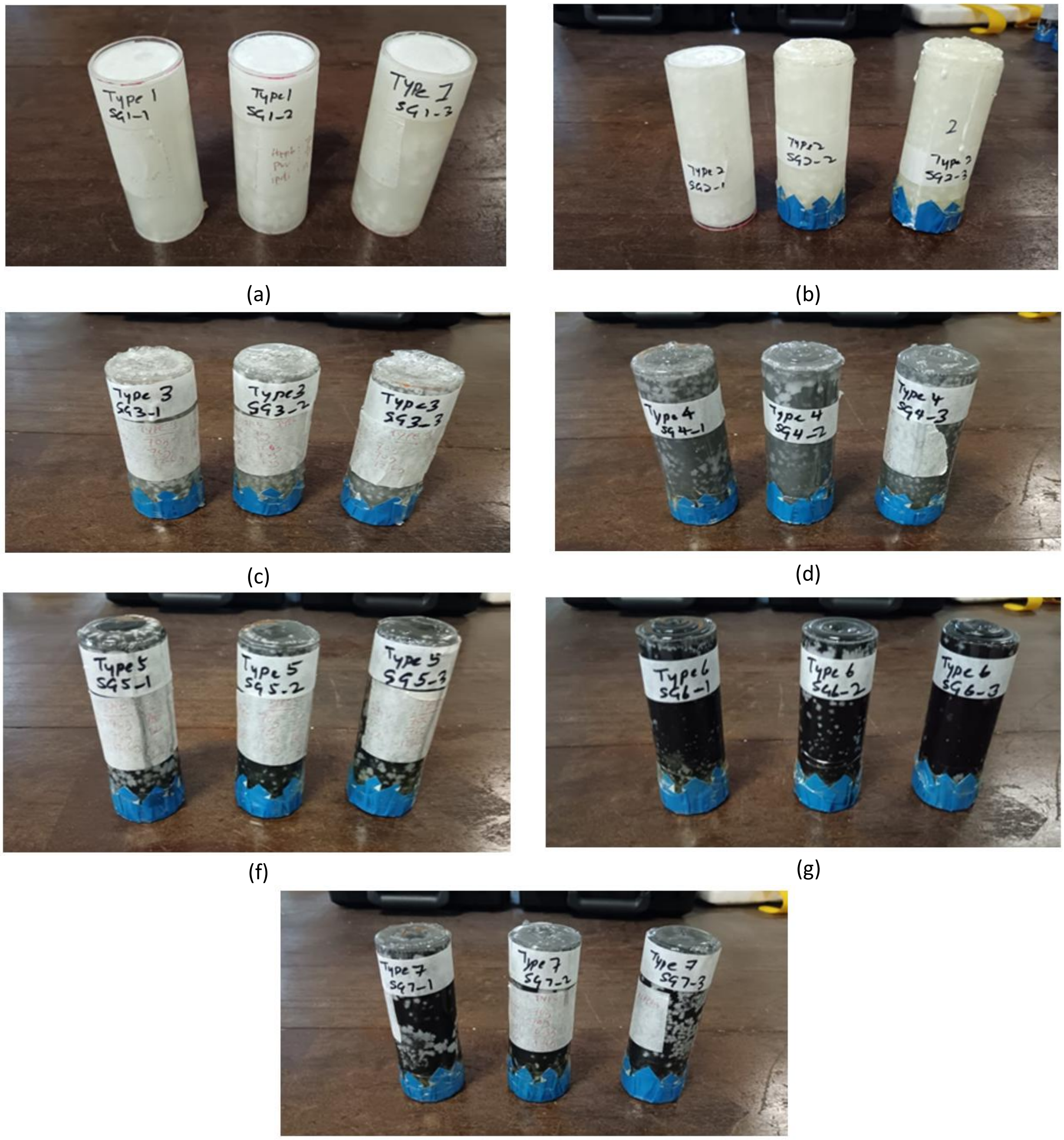
2.3 Fuel Fabrication and Experimental Setup

There will be 21 solid fuel test samples with seven distinct compositions were created. In these samples, High Entropy Alloy (HEA) and aluminium are combined with different fuel compositions in varying proportions, with additive particle sizes of 90 microns. Table 2 displays the precise ingredient combination.

Table 2
Fuel test samples

Sample	Fuel Composition Type
SG 1	HTPB 50%/PARAFFIN WAX 50%
SG 2	HTPB 49.5%/PARAFFIN WAX 49.5%/AP 1%
SG 3	HTPB 49%/PARAFFIN WAX 49%/AP 1%/AL 1%
SG 4	HTPB 47%/PARAFFIN WAX 47%/AP 1%/AL 5%
SG 5	HTPB 49%/PARAFFIN WAX 49%/AP 1%/HEA 1%
SG 6	HTPB 47%/PARAFFIN WAX 47%/AP 1%/HEA 5%
SG 7	HTPB 49.5%/PARAFFIN WAX 49.5%/HEA 1%

Each fuel type was tested at three oxygen inlet pressures: 100 kPa, 200 kPa and 300 kPa. Three samples were prepared for each composition to study how oxygen pressure affects combustion. This helps analyse key factors like regression rate, thrust and exit velocity. In total, 21 fuel samples were made and tested under controlled conditions. Figure 2 shows the fabricated fuel samples.

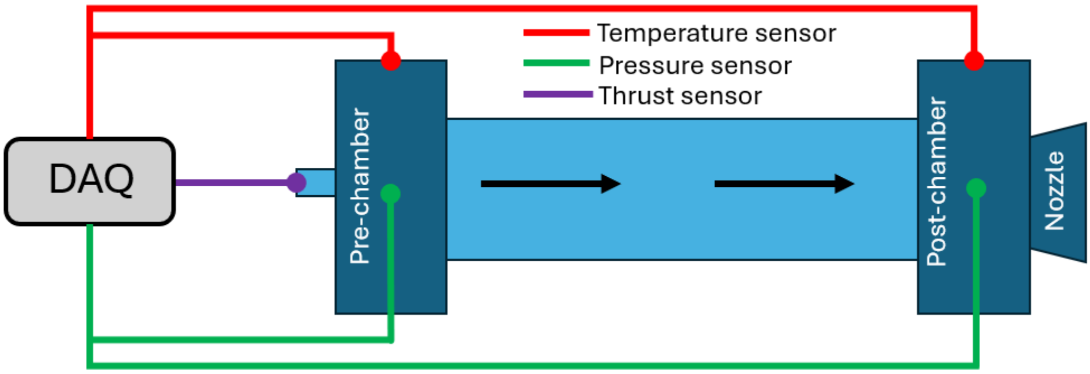


(a) (b) (c) (d) (f) (g) (h)

Fig. 2. Fabricated Fuel (a) SG1 (b) SG2 (c) SG3 (d) SG4 (e) SG4 (f) SG5 (g) SG6 (h) SG7

The hybrid rocket motor setup has various sensors to accurately measure key parameters during testing, as shown in Figure 3(b) and 3(c). Thermocouples are placed in both the pre-chamber and post-chamber to track temperature changes throughout the combustion and exhaust stages. This placement ensures precise monitoring of thermal conditions, providing essential data on the motor's heat performance.

Along with the thermocouples, pressure transmitters are installed in the pre-chamber and post-chamber to measure pressure at critical points continuously. These sensors help track pressure variations in real time, offering insights into combustion behaviour and ensuring stable operating conditions. A load cell is attached to the rocket motor assembly to measure the thrust produced during the test. This sensor captures real-time thrust data, helping assess the motor's efficiency and performance. All the sensors, including the thermocouples, pressure transmitters and load cell, are connected to a Data Acquisition System (DAQ), which records and transmits the collected data for analysis, as shown in Figure 3(a).



(a)

(b) (c)

Fig. 3. (a) Schematic diagram (b) HRM Setup without fuel (c) HRM Setup with fuel

The nozzle for this setup was made from aluminium and fabricated based on the detailed drawing shown in Figure 4.

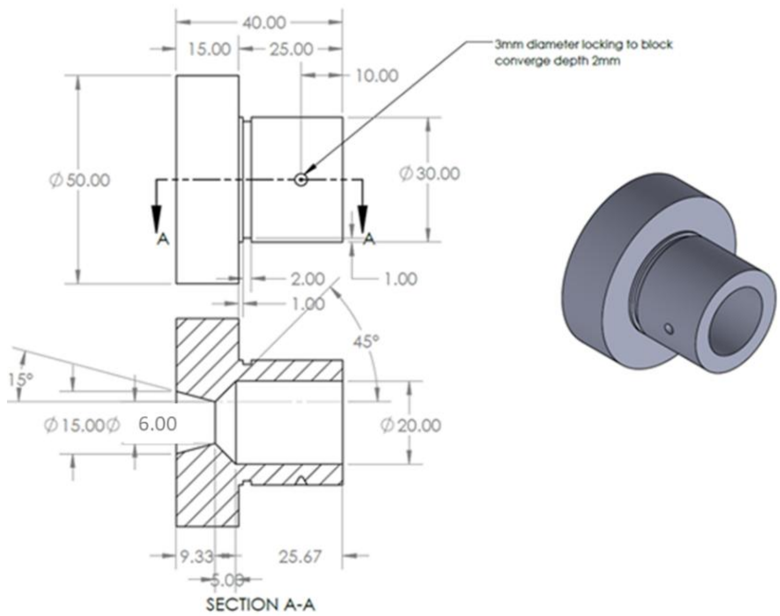


Fig. 4. Nozzle drawing details

3. Result

3.1 Performance Validation

This experimental investigation of the performance fuel HRM baseline HTPB/Paraffin blended with additives HEA has been conducted. Experimental Data fuel baseline in Table 3, Oxidizer mass flux, pressure chamber and exit pressure were used to obtain the comparison with the data calculated using Chemical Equilibrium Analysis ProPep.

Table 3
Baseline data

Oxidizer Mass Flux (Kg/m^{2}s)	Chamber Pressure (kPa)	Exit Pressure (kPa)
179.523	1096.27	58.12
190.963	1323.79	69.98
197.989	1351.37	71.43

Using the combustion conditions from the experiment, where chamber pressure and exit pressure were recorded, Table 4 compares the thrust and specific impulse between the experimental data and CEA ProPeP calculations. The comparison accuracy is affected by the fuel formulation data available in the CEA ProPeP library.

Table 4
Comparison of experimental with CEA ProPep

Oxidizer Mass Flux	Thrust (N)			Specific Impulse (S)		
	Experimental	CEA	% Error	Experimental	CEA	% Error
179.523	56.230	53.004	6.086	100.375	94.649	6.050
190.963	67.736	57.063	18.704	112.395	94.718	18.663
197.989	69.084	59.602	15.908	109.756	94.725	15.868

This table compares the experimental results with the predictions from CEA ProPeP for thrust and specific impulse at different oxidizer mass flux values. It also shows the percentage error between them. The thrust values from the experiment range between 56.230 N and 69.084 N, while the CEA ProPeP predictions are lower, between 53.004 N and 59.602 N. The difference between them varies from 6.086% to 18.704%, with larger errors at higher oxidizer mass flux values. For specific impulse, the experimental values are between 100.375 s and 112.395 s, while the CEA ProPeP predictions remain nearly the same, around 94.649 s to 94.725 s. The error in specific impulse also increases as oxidizer mass flux rises, ranging from 6.050% to 18.663%. Overall, the experimental results are higher than the CEA ProPeP predictions and the difference grows as the oxidizer mass flux increases. This may be due to differences in fuel properties, experimental uncertainties or factors not considered in the CEA ProPeP model. The result also has been illustrated in Figure 5.

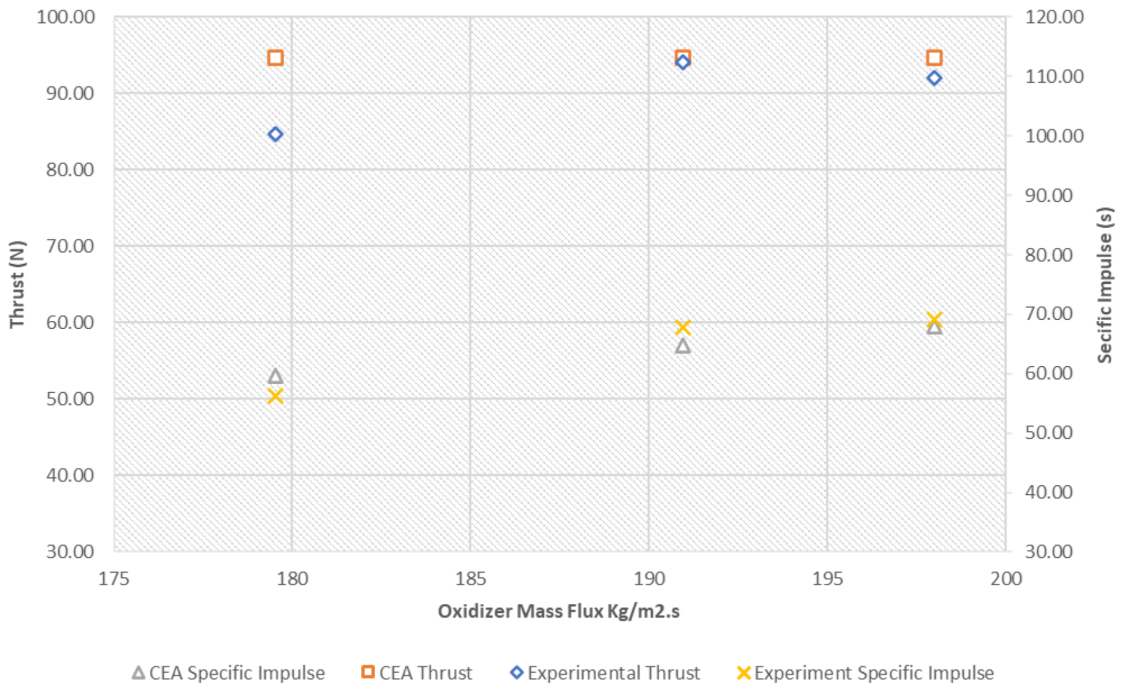


Fig. 5. Comparison of experimental with CEA ProPep

3.2 Experimental Result
3.2.1 Regression rate

The regression findings presented in Figure 6 and the displayed data illustrate the enhancement trend. All fuels increase the regression rate when combined with additives. The augmentation percentages vary among them.

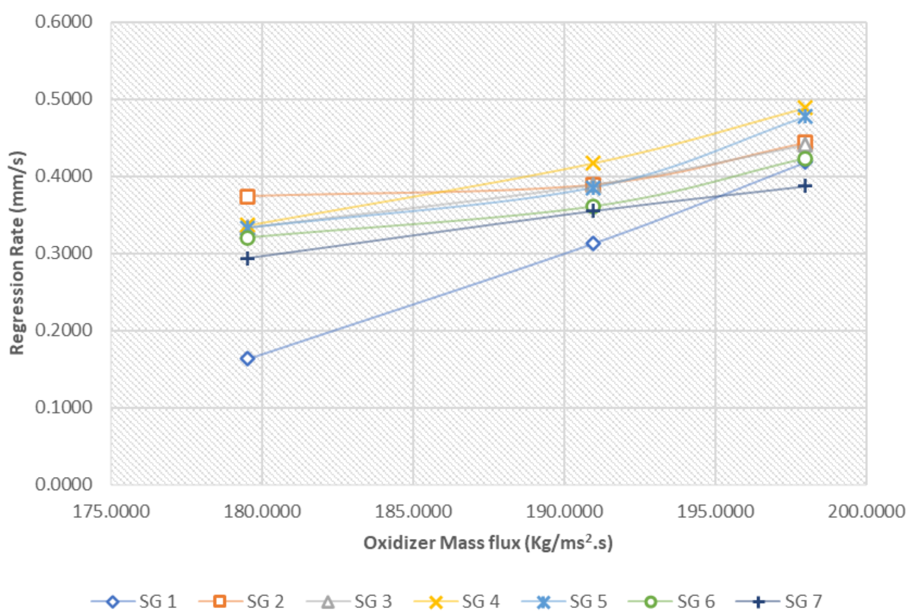


Fig. 6. Regression rate vs oxidizer various cases

The maximum enhancement percentage of 128% is observed in the fuel blended solely with AP in Table 5, maintaining the highest enhancement percentage compared to other additives. HEA appears less promising as an energy supplement compared to AP and AL, with just 79% efficacy. Even with elevated oxidizer mass flux, there is no improvement relative to the baseline fuel. With an AP concentration of 1% in HEA, the enhancement percentage increased by 103% compared to pure HEA alone.

Table 5
Regression rate enhancement percentage

Fuel	Regression Rate Enhancement		
Oxidizer Mass Flux	179 Kg/ms^2	190 Kg/ms^2	197 Kg/ms^2
SG 2	128%	24%	6%
SG 3	104%	24%	5%
SG 4	88%	33%	17%
SG 5	103%	23%	14%
SG 6	95%	15%	1%
SG 7	79%	13%	-8%

Figure 7 illustrates the combustion behaviour of the fuel containing 1% HEA additive.

2 second

5 second

10 second

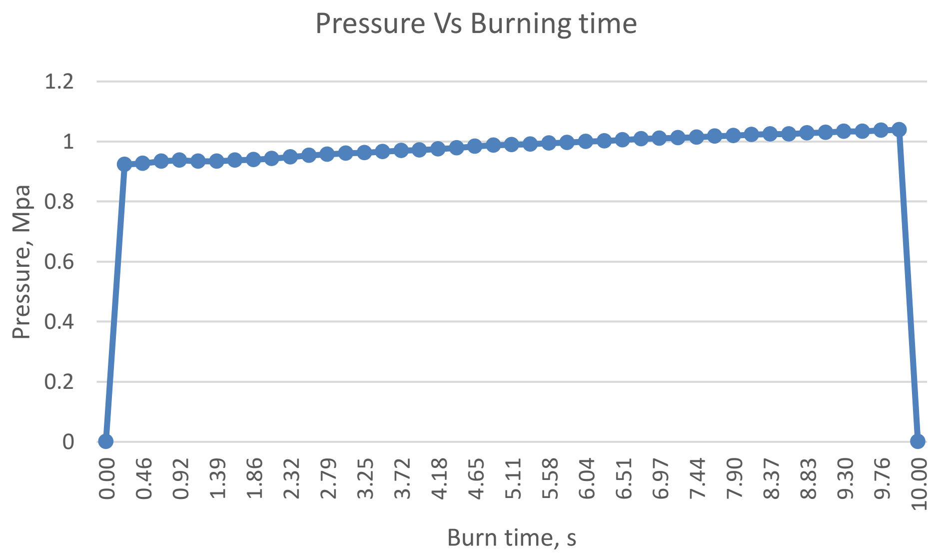


Fig. 7. Burning of HEA 1% (SG5)

A higher concentration does not guarantee that the regression rate will achieve an optimal situation, when the enhancement percentage diminishes to 95%. AL has been demonstrated as an effective additive for improving regression rates in previous studies, with AL's regression improvement comparable to that of HEA combined with AP at 104%.

The results highlight the importance of a well-optimized balance between thermal and mass transfer processes. Formulations with AP generally display superior regression rates, suggesting that their effective distribution and efficient mass transfer processes compensate for the negative implications of increased oxidizer mass flux. Conversely, formulations containing HEA or AL exhibit performance variations depending on the oxidizer flux. Their effectiveness may be reduced under conditions where diffusion limits the heat transfer required for effective fuel vaporization, especially at higher velocities.

3.2.2 Thrust

The thrust trend of all type fuels is in Figure 8 and Table 6 provides thrust performance data for various fuel combinations as a percentage change compared to a baseline fuel blend under varying oxidizer mass flux conditions. Each entry indicates how the specific blend affects thrust, which could be critical for performance evaluation in propulsion systems.

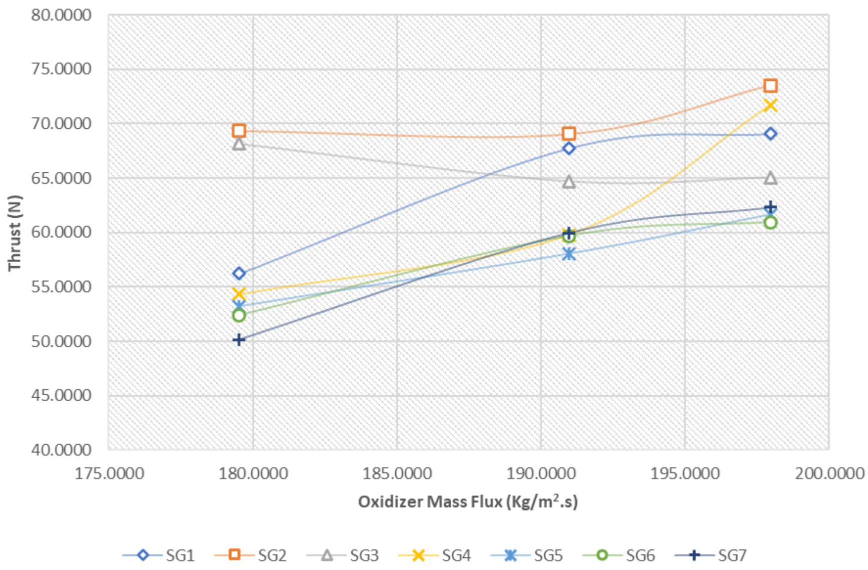


Fig. 8. Thrust vs oxidizer various cases

Table 6
Thrust performance percentage

Fuel	Regression Rate Enhancement		
Oxidizer Mass Flux	179 Kg/ms^2	190 Kg/ms^2	197 Kg/ms^2
SG 2	23.30%	1.90%	6.40%
SG 3	21.20%	-4.50%	-4.90%
SG 4	-3.60%	-11.70%	3.70%
SG 5	-5.30%	-14.30%	-10.70%
SG 6	-6.88%	-11.90%	-11.10%
SG 7	-10.70%	-11.70%	-9.70%

The thrust performance of different fuel formulations varies significantly depending on the oxidizer mass flux levels, highlighting the complex interactions between fuel components and combustion conditions. The SG7 formulation consistently exhibits a decline in thrust performance across all oxidizer mass flux levels. This suggests that combining HTPB, plasticizer (PW) and HEA negatively affects combustion efficiency, possibly due to increased viscosity or reduced burning efficiency. The SG2 formulation, containing ammonium perchlorate (AP), shows a significant thrust improvement (23.3%) at low oxidizer mass flux. However, its performance declines at mid (1.9%) and high (6.4%) oxidizer levels, indicating that AP's benefits diminish under higher oxidizer concentrations, possibly due to combustion stability challenges.

The SG5 and SG6 blends, which combine HEA with AP, show a reduction in thrust performance across all oxidizer conditions, with the largest drop occurring at higher oxidizer flux. This indicates that while HEA may provide benefits such as burn rate control and thermal stability, it negatively impacts thrust when mixed with AP. The SG3 and SG4 formulations, incorporating aluminium (AL), yield mixed results. A 1% AL addition improves thrust at low oxidizer flux (21.2%), confirming aluminium's role in enhancing energy release. However, a 5% AL addition produces inconsistent results, reducing performance at mid-range oxidizer levels but increasing thrust at high flux (3.7%). This suggests that optimal AL concentration requires further tuning for stable performance across different oxidizer conditions.

These findings emphasize the need to balance fuel composition to optimize thrust performance carefully. The interactions between HTPB, AP, HEA and AL must be evaluated in relation to oxidizer mass flux to achieve the desired propulsion characteristics.

3.2.3 Specific impulse

Figure 9 provides thrust performance for various fuel combinations and percentage change compared to a baseline fuel blend under varying oxidizer mass flux conditions.

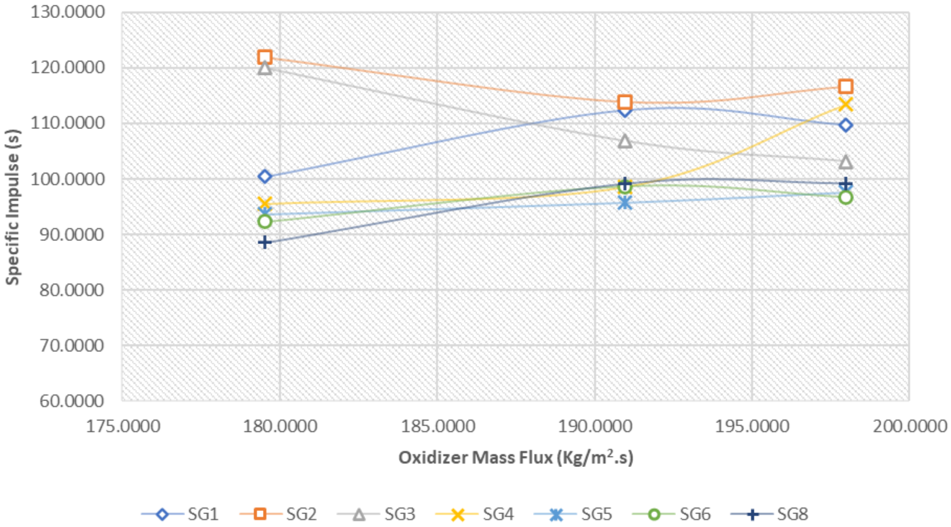


Fig. 9. Specific impulse vs oxidizer various cases

The specific impulse performance of different fuel formulations varies depending on oxidizer mass flux levels, highlighting the influence of fuel composition on combustion efficiency. The SG7 formulation consistently exhibits poor performance across all oxidizer conditions. The negative percentages suggest that HEA reduces the efficiency of converting chemical energy into kinetic energy, likely due to combustion instability or ineffective energy release. The SG2 formulation, containing ammonium perchlorate (AP), shows a significant improvement (21.3%) in specific impulse at low oxidizer mass flux, indicating enhanced energy conversion efficiency. However, its performance declines drastically (1.3% and 6.2%) at mid and high oxidizer levels, suggesting that higher oxidizer concentrations may disrupt combustion stability or reduce mixing efficiency.

The SG5 and SG6 blends, which combine HEA with AP, negatively impact specific impulse across all oxidizer levels. The largest reductions occur at higher oxidizer mass flux, indicating that HEA may cause incomplete combustion or inefficient reaction rates under elevated oxidizer conditions. The SG3 and SG4 formulations, incorporating aluminium (AL), show mixed results. A 1% AL addition improves specific impulse significantly (19.6%) at low oxidizer flux, suggesting enhanced energy release and combustion efficiency. However, a 5% AL addition leads to a significant drop in specific impulse, likely due to inefficient combustion or excess aluminium that does not fully react at higher oxidizer levels.

Overall, these results emphasize the importance of optimizing fuel composition to achieve efficient energy conversion and stable combustion. The balance between AP, HEA and AL is crucial in maximizing specific impulse while maintaining combustion stability across different oxidizer conditions.

4. Conclusion

This study aimed to investigate the enhancement of regression rates by incorporating High Entropy Alloy (HEA) energetic additives in hybrid rocket motors utilizing HTPB/Paraffin fuel. The findings indicate that the selection and concentration of additives, particularly HEA, are crucial in influencing fuel performance. The 79% improvement in regression rate with HEA from your results demonstrates that while HEA may not enhance the burning rate as dramatically as AP (which shows a 128% boost), it still provides important benefits. Specifically, HEA improves the thermal stability and ensures more uniform burning, both of which are critical for consistent and reliable performance in hybrid rocket motors. These qualities are especially important in situations where the rocket operates under changing temperature conditions, like in space or high altitudes. So, while HEA's impact on the regression rate is lower compared to AP, its ability to enhance combustion stability and uniform fuel burn makes it a valuable additive for ensuring the rocket's performance over time. The study successfully examined the effects of HEA on regression rates, demonstrating that AP consistently outperformed other additives, achieving superior thrust, specific impulse and regression rates. Aluminium (Al) performs better than HEA because aluminium burns and releases a lot of energy, which boosts thrust, especially at higher oxidizer mass fluxes. HEA, on the other hand, doesn't release as much energy but helps make combustion more stable and consistent. In terms of heat of reaction, aluminium releases more heat, improving thrust performance, while HEA helps keep combustion stable without significantly increasing energy output. While aluminium can cause combustion instabilities if not mixed well.

The results highlight the need for further research into combustion chemistry, exhaust velocity and heat transfer characteristics governing these performance variations. Future studies should include a broader range of oxidizer mass fluxes and additive concentrations to gain deeper insights into the factors influencing hybrid rocket motor performance. Additionally, direct measurement of exhaust velocity under different operating conditions is recommended, as it could provide a more accurate assessment of its impact on thrust and specific impulse trends. Techniques such as pitot tubes, Laser Doppler Velocimetry (LDV) and mass flow meters could be employed to refine these measurements. Moreover, improvements in fuel manufacturing processes and ensuring sufficient sample production for each test could enhance result consistency and strengthen the statistical reliability of findings. By implementing these recommendations, future research can provide a more comprehensive understanding of fuel composition interactions, operational conditions and overall hybrid rocket motor performance, ultimately contributing to developing more efficient and optimized hybrid rocket propulsion systems.

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