EXPERIMENTAL EVALUATION ON THE EFFECTS OF ENERGETIC ADDITIVES IN THE HYBRID ROCKET FUEL

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ABSTRACT

This paper evaluates the viability of employing paraffin wax including energetic additives as solid fuel in a hybrid rocket. In this paper, three distinct fuel compositions were used to compare the augmentation of the regression rate. Hybrid rockets combine the best characteristics of solid and liquid rockets, and they provide a multitude of advantages, such as safe handling and storage, a wider variety of fuel, a lower price, and enhanced dependability. However, it has a key drawback that hinders performance: a low regression rate. An earlier study found that doping the fuel with energetic additives such as aluminium, boron, hydrogen, and ammonia might increase the pace of regression. These nanoparticles will enhance evaporation and combustion efficiency, hence accelerating regression. According to the data, using aluminium increases regression rates by up to 21.2%, followed by using magnesium (19.9%), and iron (8.7%), which has the smallest increase in regression rates. According to this study, adding energetic materials to the fuel of hybrid rocket motors has improved the regression rate problem.

KEYWORDS

Hybrid Rocket Motors; Energetic additives; Regression rate; Hybrid rocket fuel

NOMENCLATURE

A = Area (m^2)
a = Regression rate coefficient
F = Thrust force (N)
G = Mass flux ($\mathrm{kg/m^2.s}$)
g = Gravitational constant ($\mathrm{Nm^2/Kg^2}$)
I_{sp} = Specific impulse (s)
L_p = Port length (m)
m = Fuel length exponent
m_{final} = Final mass (kg)
$m_{initial}$ = Initial mass (kg)
$\dot{m}$ = Mass flow rate
N = Number of ports
n = Mass flux exponent
P_{atm} = Ambient pressure (Pa)
P_c = Chamber pressure (Pa)
P_e = Exit pressure (Pa)
P_o = Stagnation pressure (Pa)
R = Gas constant (J/kg.K)
$\dot{r}$ = Fuel regression rate (m/s)
r_{after} = Radius after (m)
r_{before} = Radius before (m)
T_c = Chamber temperature (K)
t_b = Burning time (s)
V = Velocity (m/s)
γ = Specific heat ratio
ρ = Density
P_{atm} = Ambient pressure (Pa)

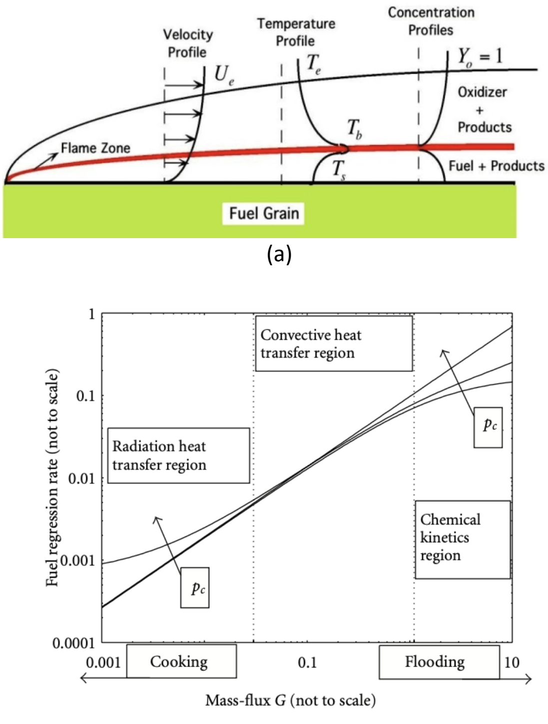
INTRODUCTION

Since the initial foundation for rocket development, rocket propulsion has made significant strides forward. It has undergone several transformations and developments, spanning from conventional to unconventional, from conventional to unconventional, from conceptualization to actualization in a variety of methods. Variations in this category include the energy source utilized to generate thrust, the engine system, the propellants used in the system, and many more. It is the energy deposited when propellants are combusted in a chamber, and the hot gas is thrust via a nozzle that is the core idea of rocket propulsion [1], [2]. In this research, the utilization of energetic additives as a fuel and their effect on the performance of a hybrid rocket, which uses a combination of solid fuel and a liquid oxidizer, is investigated. This sort of rocket has received considerable attention due to its advantages, including greater safety, dependability, simplicity, cheaper cost and fuel flexibility. The most critical features are the ability to restart and throttle the engine. These features will not be possible with a solid rocket motor [3]. A liquid rocket engine has the ability to be approved and throttled. However, the development of such a system is complex and expensive. Despite this, one of the most significant issues that must be addressed is the low regression rate.

There are a variety of methods for increasing the regression rate, including the use of energetic additives, end-burning method, and the change of port forms [4-6]. The purpose of this study is to provide a more detailed explanation of the application of energetic additives as an enhancement when mixed with the fuel.

The rate of regression is dependent on the burnt propellant gas's viscosity, the enthalpy difference between the flame zone and the wall, the blowing factor, the density of the fuel, solid fuel vaporization, and the velocity of the gas at the flame zone boundary layer [7]. Fuel compositions must be changed as a result to revitalize the thermochemical process. Therefore, the fuel regression rate in static firing using pure paraffin wax solid fuel doped with energetic additive are being explored in this study.

Energetic additives that are involved for this particular research include Al, Mg and Fe. In the presence of these nanoparticles, there is a high rate of radiative heat transmission to the molten layer atop the solid fuel, which accelerates evaporation and improves the combustion efficiency at the same time. These nanoparticles are believed to increase the specific impulse, density specific impulse, and regression rate of the solid fuel [8]. On the basis of their chemical properties, it is considered that the varied energy additives can enhance the regression rate. Boundary layer combustion is caused by fuel evaporation. Figure 1 (a) depicts the major combustion zone and Figure 1 (b) depicts a very tiny flame zone is demonstrated to be located within the boundary layer. Two methods of heat transfer that allow fuel to vaporize are convection and radiation from the flame zone. The vaporized fuel is transferred from the hot fuel surface to the flame zone.



(a)

(b)

Figure 1: Mechanism of hybrid fuel combustion (a) and typical regression rate behavior (b) [2]

An unburned oxidizer is delivered from the main oxidizer stream to the flame through turbulent diffusion. The stoichiometric conditions of the reaction dictate the location of the flame within the boundary layer. The pace of the combustion process, which is governed by pressure and temperature, determines the thickness of the flame. The creation of the boundary layer is influenced by chamber pressure, gas temperature, gas composition, mass flow rate, port length, and port diameter. Traditional combustion is limited by diffusive heat transport to the fuel surface, resulting in low regression rates. Therefore, a few approaches should be implemented to pace the regression rate. Several methods have been investigated and tested in order to improve the regression rate of hybrid propulsion systems. It has been tried through the use of unconventional design techniques. The researchers enhanced oxidizer-fuel interaction and dwelled duration by constructing the hybrid grain with many ports. Another possibility is to use novel oxidizer injection methods, like as swirl injectors and vortex hybrid engines, to enhance the mixing and turbulence of the propellants inside the combustion chambers. On the chemical side, which this paper will focus, energetic particles have been doped into the hybrid fuel matrix to increase the total regression rate [4].

As previously noted, one of the few ways to increase the regression rate in a conventional hybrid rocket engine is by the addition of energetic additives to the fuel. The rate of regression is affected by component properties (e.g., reactivity, heat of oxidation, density) and particle characteristics (e.g., shape, dimension, coating). This section will examine the theory and research on several types of energy additives conducted by various researchers. An energetic additive is a substance that contains energetic particles such as metals and hydrides that energizes the solid fuel grain. This technology sparked attention in the rocketry world in the 1950s when it was discovered that incorporating aluminium into the solid propellant improved the rocket's performance. However, the use of energetic elements in explosives dates all the way back to 7 A.D., when the Byzantines of Constantinople produced 'Greek Fire,' and the use of energetic materials in explosives began with the introduction of black powder, popularly referred to as gun powder [9].

Metallic particles provide a number of advantages, including the capacity to moderate pressure oscillations, raise the specific impulse, and also boost propellant density. It is hypothesized that including additives such as metal and boron into the fuel matrix will result in a decrease in the heat of gasification. Moreover, it would help mitigate the impact of mass blocking. Taken together, this will result in an increase in the rate of fuel regression [10]. Furthermore, it is discovered that aluminium and boron exhibit desirable combustion properties, particularly in the realm of HREs. They generate a great amount of heat during combustion or energy release and have a high density. They might theoretically overcome the difficulties inherent in traditional HREs. Metallic powders generate substantial energy during burning, raising the adiabatic flame temperature and, subsequently, the propellant gravimetric specific impulse (Is), despite an increase in the average molar mass of the combustion products. Metals also improve the propellant density, hence increasing the propellant volumetric real impulse (Iv). Both of these impacts are significant for a space propulsion mission. In Figure 2, the volumetric heat of oxidation or combustion with oxygen is compared between inert HTPB and a variety of different energetic additions. In comparison to other metal additions, the HTPB has no promising properties. Metal additives have a high rate of volumetric heat oxidation, indicating that their inclusion indicates their capacity to give a substantial quantity of energy to rocket engines [9, 10].

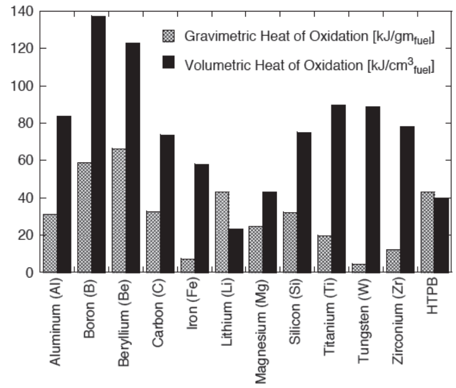


Figure 2: HTPB and metal additives relative comparison [9]

When designing energetic additives, a few of their properties must be considered. These include the following: (1) The volume of solid oxide in molar proportion to the volume of solid metal, (2) Coefficients of thermal expansion of solid metals and oxides in relation to one, (3) The metal's melting point, (4) The oxide's melting point, (5) The molten oxide's solubility in the molten metal, (6) The metal's boiling point and (7) The oxide's boiling point. A research and test are conducted to determine the rate of regression of HREs. The study employs a fire test to determine the combustibility of HTPB and HTPBs doped with ultrafine activated aluminum powder (UFAL), where most of the articles range in size from 0.05 - 0.1µm. When 20% of the total fuel is doped with HTPB, the regression rate increases by roughly 40% and the mass flux increases by 70% [11]. This paper mainly focuses on three metal energetic additives which are; Aluminum, Magnesium and Iron. Next section will cover all the methodology and experimental setup for a lab-scale static firing.

METHODOLOGY

A fuel doped with energetic additives is believed can improve the regression rate, which helps the heat of vaporisation of the fuel. In this experimental setup, a solid fuel grain which is a pure paraffin wax, and a few energetic additives are chosen to be doped with the baseline fuel which are, Aluminum (Al), Magnesium (Mg) and Iron (Fe) will be employed. Aluminium is chosen as it is the most investigated component for solid fuel formulations with high oxidation temperature, high density, and ease of ignition. Due to the scarcity of datasheets on the characteristics of these alloys and the fact that the experimentation on these alloys is still in its infancy, not many additives are discovered to have a complete dataset to be employed as chosen additives to be doped with the fuel for the experimental setup.

This section outlines the design of the hybrid rocket test facility's individual components. It is critical to develop and construct a specialized system that will regulate the oxidizer flow, combustion process, data gathering, and ignition system at this stage. The configuration demonstrates a feasible system for the planned hybrid motor. In this experiment, eight major components will be involved, which are; (1) Rocket casing, (2) Fuel grain, (3) Nozzle, (4) Feeding system, (5) Test stand, (6) Data acquisition system, (7) Feed and end caps and (8) Ignition system. These relations are utilized to determine the grain configurations' geometry. Prior to that, the mission need must be specified in order to determine the required fuel mass.

$$\dot{m}_{prop} = \frac{m_{after} - m_{before}}{t_b} \tag{1}$$

$$\dot{r} = \frac{r_{\text{after}} - r_{\text{before}}}{t_b} \tag{2}$$

$$V = \sqrt{\frac{2(P_{\text{o}} - P_{\text{atm}})}{P_{\text{o}}}} \tag{3}$$

$$\dot{m}_{ox} = \rho_o AV \tag{4}$$

$$G_0 = \frac{\dot{m}_o}{NA_p} \tag{5}$$

$$V_{\text{exit}} = \sqrt{\frac{2\gamma RT_c}{(\gamma - I)}\left\{1 - \left(\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right\}} \tag{6}$$

$$F = \dot{m}_{\text{prop}} V_{\text{exit}} + (\rho_{\text{exit}} - \rho_{\text{atm}})A \tag{7}$$

$$I_{\text{sp}} = \frac{F}{\dot{m}_{ox} g_o} \tag{8}$$

The following empirical relationship may be used to determine the length of the fuel grain:

$$L_p = \frac{\dot{m}_{fuel}}{N\rho_{fuel} a(G_{ox} + G_{fuel}) n_{P_{pi}}})^{\frac{1}{m+1}} \tag{9}$$

Dimension and Specifications

Paraffin-based fuels require a fuel case due to their low melting point. The casing specification in Table 1 is determined by the predicted size of the fuel, and the installation of the case on the testbed is depicted in Figure 3.

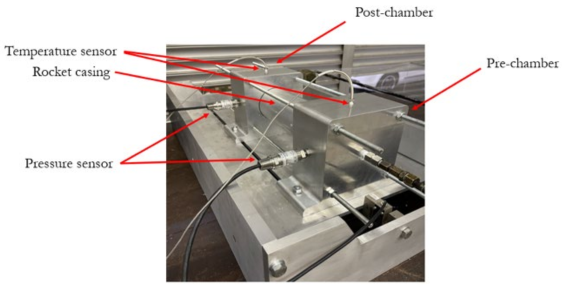


Figure 3: Testbed with rocket casing

Table 1: Specifications of the rocket casing

Material	Aluminum
Length (m)	0.30
Inner diameter (m)	0.1016
Outer diameter (m)	0.10166
Mass (kg)	80

As mentioned in the previous section, the fuel used for the experimental setup is the pure solid fuel grain; pure paraffin, 1% Al, 1% Mg and 1% Fe. All energetic additives will be doped with pure paraffin. The primary criterion for selecting a fuel is the availability of resources; consequently, paraffin wax was chosen as the fuel. Based on past research, paraffin wax appears to be the most promising material for lab-scale hybrid rockets. Throughout the experiment, a single circular port will be used. 8kg of paraffin wax in the shape of blocks may provide 4 fuel molds. Bubbles begin to emerge throughout the molding process when the paraffin wax solidifies. Pouring procedures should be used with caution to resolve the issue. The molded paraffin wax is put carefully into the case to avoid cracking. The paraffin wax fuel parameters are derived from the equations in section 5 and are displayed in Table 2, while the products are illustrated in Figure 4. For this project, only one mold of pure paraffin wax is needed. The other three will be doped with 1% energetic additives which is 20g for each metal element; Al, Mg and Fe and final doping fuel is tabulated in Table 3. The primary rationale for using a non-homogeneous fuel is to avoid uniform combustion.

Figure 4: Paraffin fuel that has been moulded

Table 2: Specifications of the paraffin wax

Material	Paraffin wax
Length (m)	0.28
Inner diameter (m)	0.033
Outer diameter (m)	0.100
Mass (kg)	2 kg

Table 3: Fuel specifications for HRM

Fuel Type	Additives (by wt%)	Additives concentration	Weight (kg)
1	None	None	2.189
2	1% Aluminium	Homogeneous	2.307
3	1% Magnesium	Homogeneous	2.230
4	1% Iron	Homogeneous	2.143

The nozzle is made of an aluminum rod with a convergent-divergent type and 14 mm is the smallest throat diameter that can be machined. Fabrication of the nozzles is performed using a CNC lathe. The detailed drawings of the nozzle are displayed in Figure 5.

The feeding mechanism system comprises the tube, hose, steel reducer, steel join, solenoid valve, ball valve, and self-pressurized oxygen gas tank. A 10L oxygen gas (GOX) tank was chosen as the oxidizer due to its simplicity and lack of injectors. Another factor is, this oxidizer is more readily available on the market and easier to replenish than other oxidizers as portrays in Figure 6.

A pressure regulator is employed to control the high-pressure oxygen gas from the oxygen tank to the combustion chamber. A ball valve manages the oxidizer flow into the chamber. In order to assure safety, the ball valve must be able to endure the tank's high pressures. The ignition system used a simple match. Steel wool is wrapped around the matches and then attached to a copper wire. Steel wool is connected to a basic electric circuit that generates a current and Figure 7 display the igniter used during the evaluation.

The test stand is constructed from an aluminium block that was CNC milled. A groove is formed to guide the tray, and eight smooth bearings are positioned on the side. Two slots are cut into the tray to accommodate fuel of varying lengths. Slots at the front and rear of the test stand accommodate the feed line and plume gas. Figure 8 demonstrates a sample of a manufactured test stand.

For data acquisition system, a single pressure transmitter and thermocouple are fitted at the feed and end cap. The load cell is mounted on the test bed's front. The analogue switch regulates a solenoid valve located on the gas tank and the igniter. External power is required for the pressure transmitters, load cell, and solenoid valve. Using an Arduino board, these sensors are directly connected to the computer. This project also includes the implementation of a Bluetooth system that stores all operating data on both the PC and the phone. The computer is essential to guarantee that no phone data is lost owing to the Arduino board's noises. Figure 9 illustrates the schematic diagram of Arduino connection.

RESULTS AND DISCUSSIONS

In this section, the ballistic performance as well as regression rate of each type of fuel will be discussed thoroughly. The results of static firing are visualized in Figure 10 for each kind of fuel, which comprises pure paraffin wax, PW+Al 1%, PW+Mg 1% and PW+Fe 1%. The findings show that using 1% aluminium improves fuel grain combustion more than using other additives. Its exit velocity is thus the greatest. Aluminium additives are discovered to have increased the most in the port grain's circular structure, indicating a larger quantity of fuel burned during firing (Figure 11).

Regression rate are calculated from measured radius (m) before and after burning divided by burning time, tb (s) as stated in Eq. (2) while velocity exit is obtained from Eq. (6). Lastly, thrust is acquired from velocity exit's value and a few other parameters as written in Eq. (7). Table 4 simplifies all the measurements taken during experiment to calculate the regression rate as well as other ballistic performances.

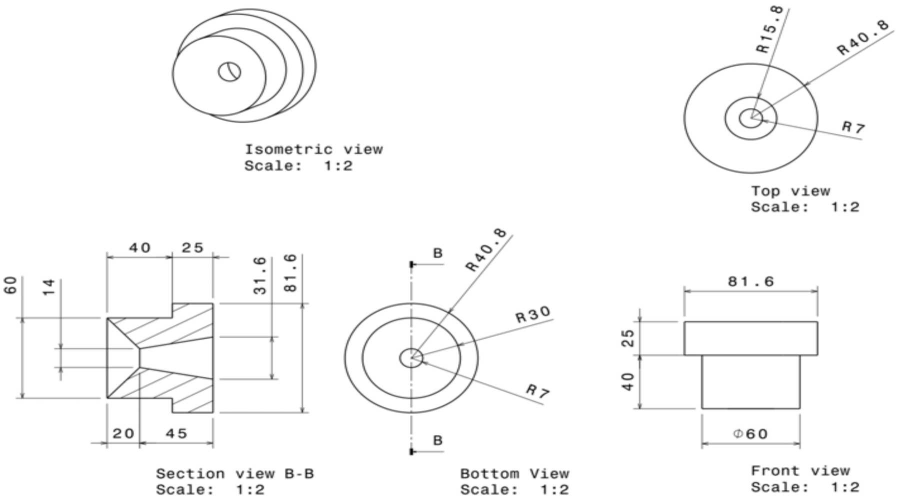


Figure 5: Drawing of the nozzle

Figure 6: Oxygen gas that has been pressurised (left) and a gas regulator (right)

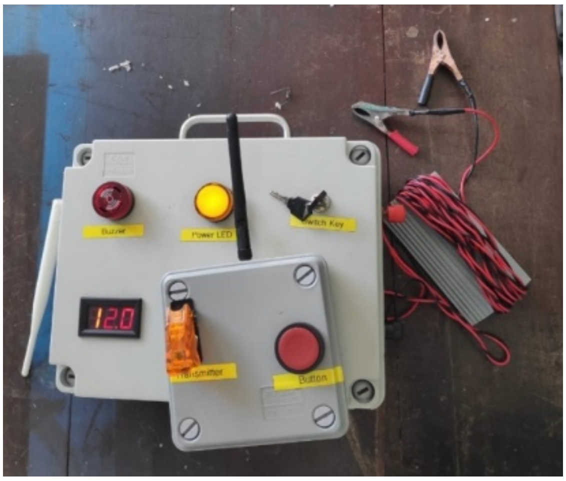


Figure 7: Ignition system

Figure 8: Testbed sample illustration

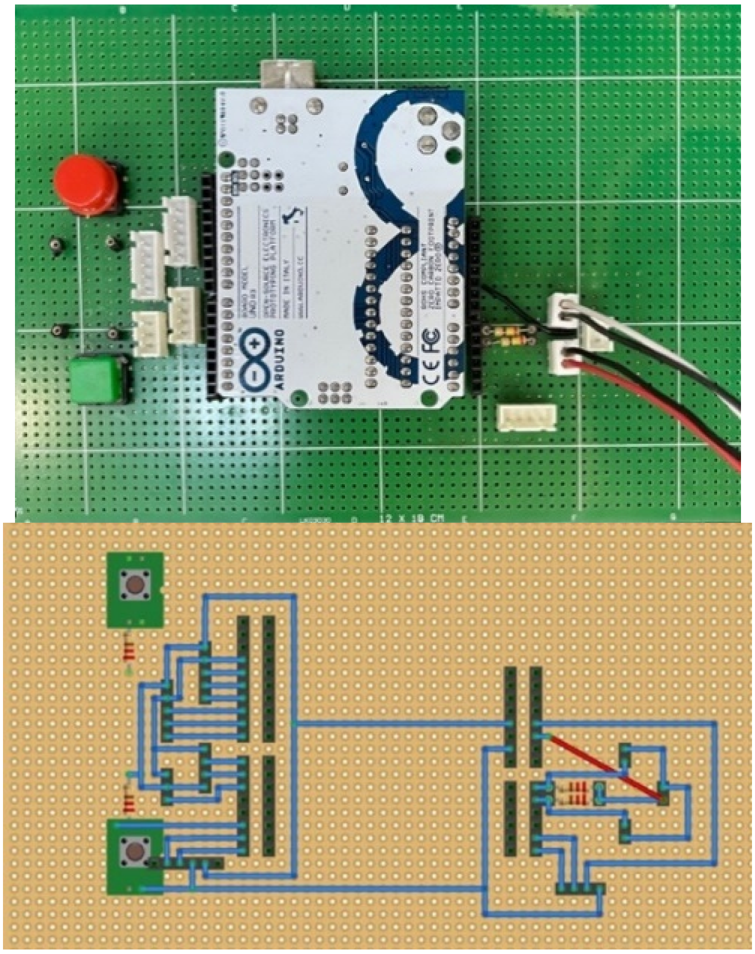


Figure 9: Arduino connection (top) and its schematic diagram (bottom)

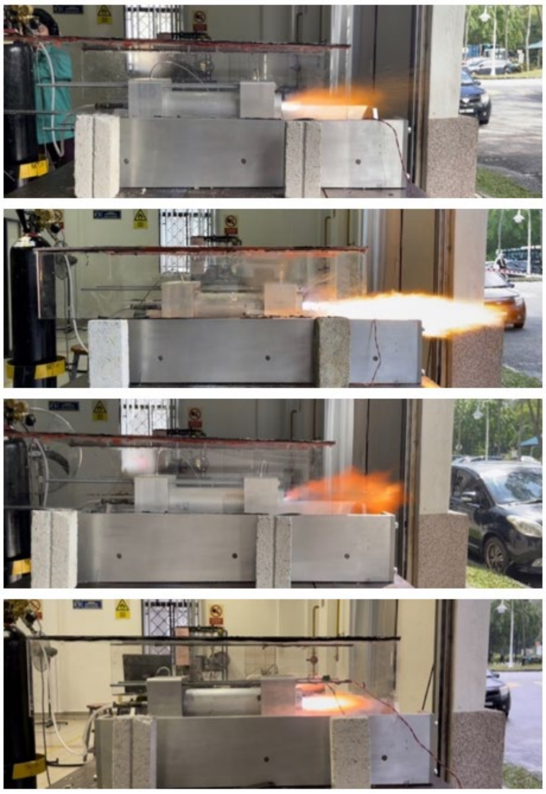
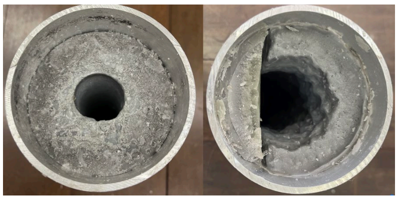


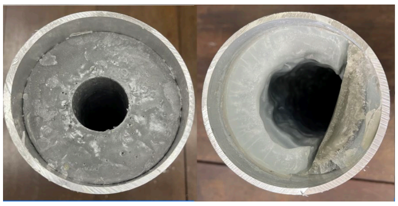
Figure 10: Static firing and the outcomes for each fuel

From the bar graph displays on Figure 12, it can be discerned that the presence of energetic additives can boost the regression rate. Even though only 1% of each energetic particles is used, the percentage of increment is more than 10% compared to the baseline, pure paraffin wax (PW) for the same burning time as portrayed in Table 5. It is believed that these energetic additives especially Aluminum, Al are considered can increase the regression rate by improving the radiative heat flux from the diffusion flame zone to the fuel surface on a micro-scale sized (Carmicino and Sorge, 2015). In addition, metal additives such as Al and Mg have the ability to greatly accelerate the rate of fuel regression in the fuel. Because of aluminum's (Al) high propensity for surface reactions, thermal feedback to the grain is amplified. The diffusive heat signature is enhanced as a result of this characteristic, which favours nucleation and fuel disruption.

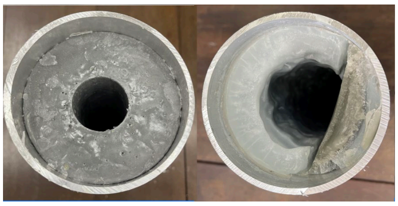
Pure paraffin wax before (left) and after (right) burning.



PW+Mg 1% before (left) and after (right) burning.



PW+Al 1% before (left) and after (right) burning.



PW+Fe 1% before (left) and after (right) burning.

Figure 11: PW product with a different metal percentage

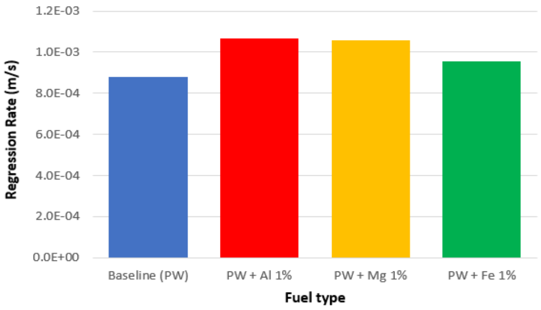


Figure 12: Bar graph of regression rate for different fuels

Table 4: Ballistic performances of hybrid rocket with different type of fuels.

Fuel type	Regression Rate (m/s)	Velocity Exit, V_e (m/s)	Thrust (N)
Baseline (PW)	0.00088	544.206	93.87
PW + Al 1%	0.0010667	773.278	1575.03
PW + Mg 1%	0.0010556	617.854	206.37
PW + Fe 1%	0.000957	558.024	95.49

Table 5: Increment of regression rate for HRM

Fuel	Increment (%)
PW + Al 1%	21.2
PW + Mg 1%	19.9
PW + Fe 1%	8.7

CONCLUSION

Hybrid propulsion using energetic-particle doping has gained appeal in the scientific community and has an enormous economic future. It provides a safe, dependable, and eco-friendly alternative to traditional systems. However, despite its propitious appearance, it is plagued by one of the most significant limitations that provides the most compelling obstacle in using hybrid propulsion systems as space launchers, namely the regression rate. When it comes to hybrid rockets, regression rate is crucial since it establishes a relationship between the thrust produced in a rocket and the overall hybrid rocket's performance. This rocket engine includes solid fuel, gaseous oxidizer, and energetic particles as additives. In this study, several energetic particles composed of various metal components are discussed. For the purpose of determining whether or not it is possible to dope energetic ingredients into hybrid rocket motors, static firings are performed on a laboratory-scaled hybrid rocket. The benefits of these particles have been considered solely in terms of their influence on regressive behaviour. There was an increase in the regression rate that ranged from 15 to 21 percent, and it was discovered that this increase was additive percent dependent. Aluminum is one of the most studied energy additives for hybrid propulsion followed by Mg and Fe doping. Al is preferred due to its comparatively high density and oxidation heat. When Al 1% is doped with paraffin wax fuel, a 21 percent increase in the regression rate was observed.

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