INVESTIGATION OF REGRESSION RATE END-BURNING TYPED HYBRID ROCKET MOTOR *

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ABSTRACT

Hybrid Rocket Motor (HRM) has a critical weakness that impacts performance: low regression rate. Due to this, extensive investigation has been done on end-burning type HRM to enhance the regression rate. Experimental works were conducted on the end-burning HRM compared to the conventional HRM. The present investigation is focused on single port HRM, paraffin wax, and gas oxygen as the fuel and oxidizer, respectively. The results show that combustion occurs only at the fuel end in end-burning mode, which permits the burning area and fuel mass flow rate to remain constant, enhancing the motor's performance and ensuring that the oxidizer-to-fuel ratio does not fluctuate. HRM performance has also been evaluated by calculating thrust and specific impulses. According to this study, end-burning HRM has a 33% less regression rate but around a 50% increase in thrust and specific impulse compared to conventional HRM. The low regression is due to the small initial combustion area. Mass flux is the more prominent factor in increasing the regression rate and thrust of the end-burning HRM compared to the fuel length. Further improvement to the design of the HRM can maximize the potential of the end-burning mode.

Keywords: Hybrid rocket, Regression rate, End-burning, Paraffin,

I. INTRODUCTION

Rocket propulsion comes in various shapes and sizes based on the rocket engine and propellant. Liquid, solid, and HRM are the three basic types of rocket engines. This research will focus on HRMs that combine solid fuel with a liquid or gas oxidizer. HRM has various advantages over conventional liquid or solid rocket propulsion systems, such as low cost, fuel management, durability, throttling capability, and environmental benefits. The throttling capability by adjusting the oxidizer mass flow rate is a significant benefit of HRMs, making them ideal candidates for adjustable thrust rockets that can be used in various applications.

HRM is entirely safe because of the solid fuel grain that is typically inert. Since the fuel and oxidizer are separated by distance and phase, hybrids have a minimal danger of explosion and few failure modes, as shown in Figure 1. The fluid oxidizer is frequently depleted in the diffusion flame area and can only reach the fuel surface when gaseous chemical kinetics are slow (low pressures). Inadvertent ignitions are avoided because pores, cracks, and flaws cannot cause a deflagration to detonation transition. Finally, because HRMs do not have the same high-temperature sensitivity as solid rocket motors, identifying a maximum expected operating pressure is not an issue [1-3].

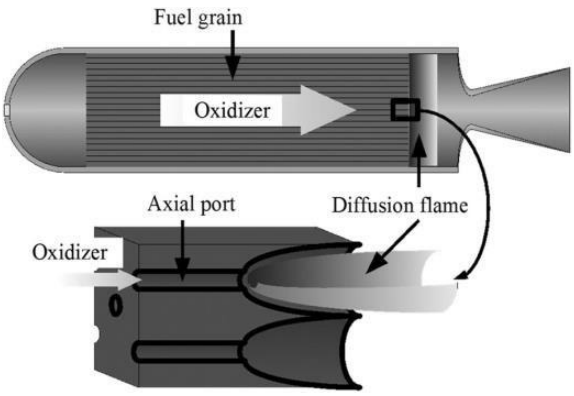

Figure 1 Schematic concept of an end-burning-type hybrid rocket [4]

The regression rate is one approach to assessing the performance of hybrid rockets. In HRM, the fuel regression rate is the rate at which the fuel surface recedes during a burn. Since different hydrocarbon fuels burned with the same oxidizer have similar specific impulses, a high regression fuel will result in a shorter combustion chamber design and a larger diameter than a low regression fuel (for a single port motor). For comparing propellants, designing a fuel grain, estimating HRM performance, and avoiding burn-throughs, accurate regression rate data is crucial [3].

In a classical HRM operation, the oxidizer sprays into the solid fuel port, and a combustion flame develops at the fuel side surface. The rate of fuel regression and the burning area varies with time, causing the oxidizer-to-fuel ratio to shift and impulse loss. For end-burning HRM, combustion only happens at the fuel end, allowing the burning area and fuel mass flow rate to remain steady, improving the motor's performance. This research will compare the end-burning mode to the conventional HRM. This research also will discuss the impact of mass flux, fuel length, and additives on the regression rate, velocity, and specific impulse. The benefits and challenges of HRM and the answers to each challenge are also highlighted.

II. SETUP AND METHODOLOGY

The design requirements are defined, such as the parameters to measure, the availability of materials, and the cost. The casing selected will be acrylic for better viewing in the combustion chamber. The design of the HRM was based on the preliminary decisions and assumptions stated in Table 1 using Eq (1-9). It was determined oxygen gas would be used as an oxidizer and paraffin wax as fuel to save cost. Throughout the experiment, a single circular port will be used. The fuel parameters listed in Table 2 will be used as the baseline.

Table 1 Preliminary decisions and assumptions for the design of HRM

Parameter	Hybrid Rocket Motor
Optimal O/F	2.1
Specific heat ratio	1.2
Ambient pressure (kPa)	101.33
Oxygen density (kg/m^3)	1.429
Inlet area (m^2)	6.362e^{-5}
Exit area (m^2)	7.843e^{-4}
Gravitational acceleration constant (m/s^2)	9.81

The regression rate coefficient (a) and mass flux exponent (n) are empirical parameters derived from prior experiments. Humble et al. obtained these values, a=0.0002 and n=0.75, respectively [5].

$$C_F = \left\{ \left(\frac{2k^2}{k-1}\right)\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}\left[1-\left(\frac{P_a}{P_c}\right)^{\frac{k-1}{k}}\right]\right\}^{1/2} \quad (1)$$

$$A_t = \frac{F}{C_F P_c} \quad (2)$$

$$\dot{m} = \frac{g P_c A_t}{c^*} \quad (3)$$

$$\dot{m} = \dot{m}_o + \dot{m}_f \quad (4)$$

$$R(t) = \left[a(2n+1)\left(\frac{\dot{m}_o}{\pi}\right)^n t + R_i^{2n+1}\right]^{1/(2n+1)} \quad (5)$$

$$A_p = \pi R_i^2 \quad (6)$$

$$G_o = \frac{\dot{m}_o}{A_p} \quad (7)$$

$$\dot{r}_i = a(G_o)^n \quad (8)$$

$$L = \frac{\dot{m}_f}{2\pi R_i \rho_f \dot{r}_i} \quad (9)$$

Table 2 Rocket Motor Specification

	Fuel Casing	Fuel
Material	Acrylic	Paraffin Wax
Length (m)	0.3	0.23
Outer diameter (m)	0.1	0.097
Inner diameter (m)	0.097	0.02
Mass (kg)	0.23	1.13

Figure 2 shows the experimental setup for the static firing conducted in IIUM Propulsion Lab.

Figure 2 Experimental setup of the HRM

The thrust was directly obtained from the load cell, while the following relationships are used to compute the performance characteristics, such as regression rate and specific impulse.

$$\dot{r} = \frac{L_i - L_f}{t} \quad (10)$$

$$I_{sp} = \frac{F}{\dot{m}_f g} \quad (11)$$

The analytical results of conventional HRM will be compared to the experimental results of conventional and end-burning HRM. The regression rate trend can also be obtained for end-burning HRM and end-burning HRM doped with HEA.

III. RESULTS AND DISCUSSION

The conventional HRM was compared to the baseline, conducted using end-burning with the same fuel length and mass flux. The results show that the end-burning regression rate is lower than the conventional HRM. However, end-burning provides more thrust and specific impulse. The lower regression rate is due to the larger surface area for combustion across the fuel core for the conventional HRM compared to the small surface area at the fuel end for end-burning. A series of static firing has been made, and the results are shown in Table 3.

Table 3 Parameters for end-burning HRM

Case	GOX Mass Flow Rate (g/s)	Mass Flux, G_0 (kg/m^2s)	Fuel Length, L (mm)	Chamber Pressure (kPa)	Chamber Temperature (K)	Thrust (N)	Specific Impulse (s)	Regression rate (mm/s)
Conventional	58.8	196.78	230	212.76	315.44	94.44	132.03	1.05
Baseline	58.8	196.78	230	332.92	464.15	190.62	279.04	0.79
1	58.8	196.78	180	334.88	418.15	189.96	275.35	0.64
2	58.8	196.78	280	244.52	524.65	143.91	140.39	1.43
3	47.9	160.49	230	270.06	634.65	147.93	222.79	0.71
4	67.9	227.34	230	352.50	602.65	209.33	258.00	1.67

Case 1 and 2 was conducted with varying length, while Case 3 and 4 focused on the effect of mass flux. The highest thrust and regression rate is achieved when G_0 = 227.34 kg/ms^2. The highest specific impulse is achieved in the baseline due to the relatively high thrust and low fuel mass flow rate during combustion. Figures 3 and 4 show the regression rate against the mass flux and fuel length.

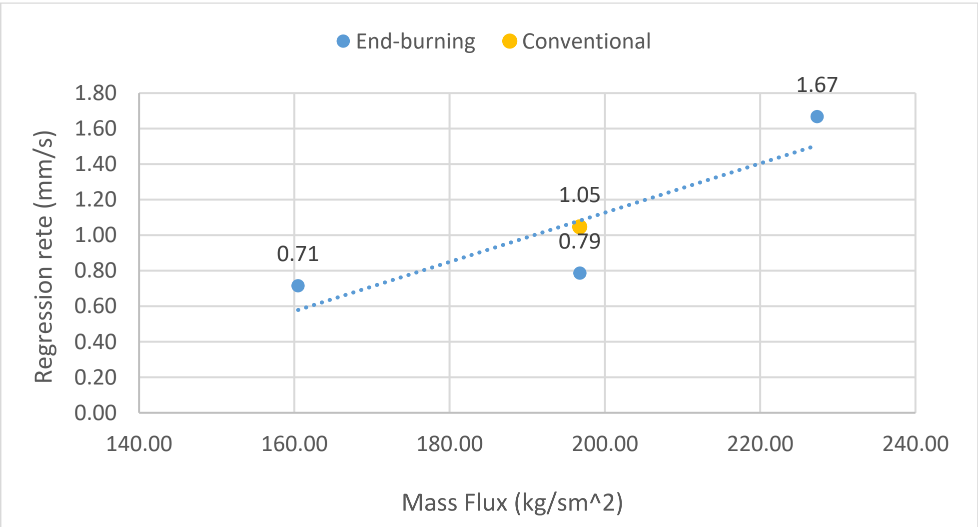

Figure 3 Regression rate against mass flux

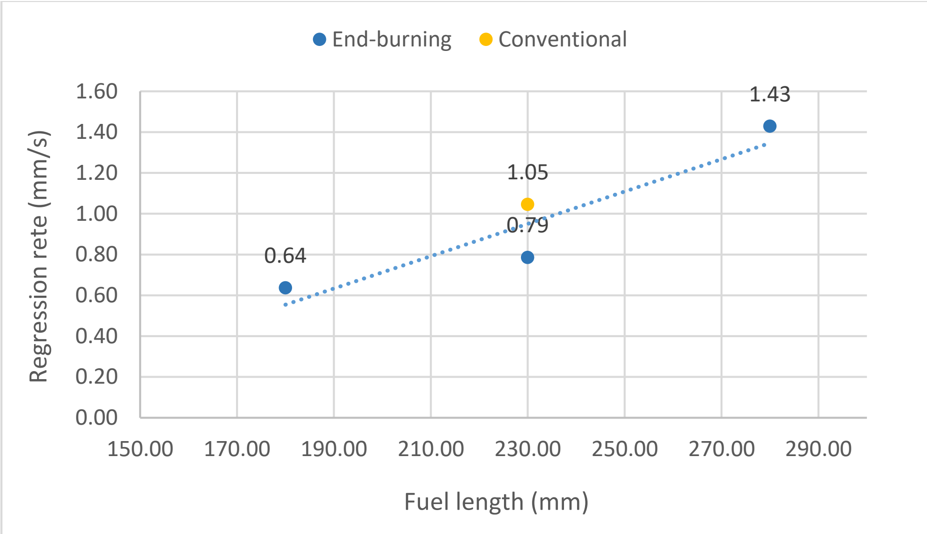

Figure 4 Graph of regression rate against fuel length

Figures 3 and 4 show that the regression rate increases with the mass flux and fuel length. However, the regression rate increases rapidly when G_0=227.34 kg/ms^2 and L=280 mm. From Figure 3, the regression rate coefficient (a) and mass flux coefficient (n) for the combustion between gaseous oxygen (GOX) and paraffin wax can be calculated using Eq. (8), which is a=3.07e^{-9} and n=2.433. Table 4 compares the experimental results' performance to the baseline.

Table 4 Performance comparison to the baseline

Case	Mass Flux (kg/ms^2)	Fuel Length (mm)	Thrust (%)	Specific Impulse (%)	Regression rate (%)
Conventional	196.78	230	-50.46	-52.68	+33.00
1	196.78	180	-0.35	-1.32	-19.00
2	196.78	280	-24.50	-49.69	+81.88
3	160.49	230	-22.40	-20.16	-9.09
4	227.34	230	9.82	-7.54	+112.17

According to the table above, conventional HRM has a 33% higher regression rate than the end-burning but around 50% less thrust and specific impulse. It also shows that mass flux influences the regression rate more than the fuel length. Longer fuel length also reduces the specific impulse and thrust.

Figure 5 showed when the HRM started to burn and during the burning. It can be seen that combustion only occurs near the nozzle, thus confirming the validity of the end-burning mode of combustion. Figure 6 shows the results after 10 seconds of burning. A lot of fuel was still left due to the short time of burning. Due to the casing being from acrylic, more extended burning periods will result in the case melting.

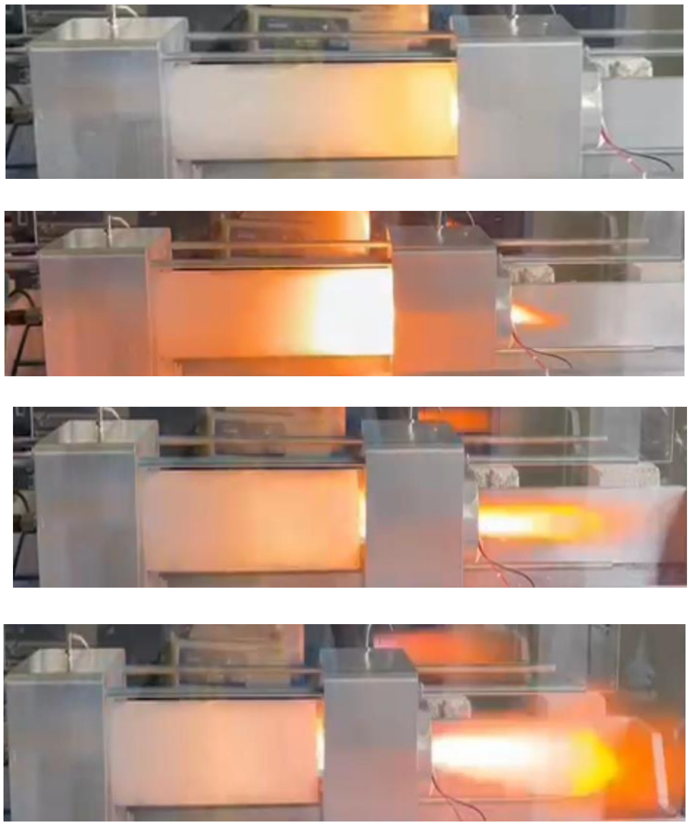

Figure 5 Sequence during static firing

IV. CONCLUSIONS

Hybrid rocket has since appealed to many people as it is safe, low-cost, has throttling capabilities, and has more propellant range that can be used. The main disadvantage of this type of rocket is the low regression rate at which the fuel surface decreases throughout a burn. Many approaches were taken to tackle this problem, and one of the methods was the end-burning mode.

This study found that the thrust and specific impulse of conventional HRM is lower than the end-burning approach. Conventional HRM has a 33% higher regression rate than end-burning but roughly 50% less thrust and specific impulse. The regression rate of end-burning HRM is lower due to the smaller initial combustion area. It was also revealed that mass flux significantly impacts regression rate more than fuel length. The specific impulse and thrust reduce as the fuel length increases. The highest thrust and regression rate was achieved with the largest mass flux, but it also caused high fuel mass flow rate, lowering the specific impulse.

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