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GEOMETRICAL EFFECTS ON FUEL REGRESSION RATE IN MULTI-PORTS DESIGN HYBRID ROCKET MOTOR

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Abstract: The characteristics of a liquid and solid rocket motor are combined in a hybrid rocket motor. It is low-cost, safe, environmentally friendly and throttling-capable. However, the primary reason why hybrid rocket performance is not preferred over other rocket propulsion is its low regression rate. This study is concentrated on lab experiments and analytical calculations related to hybrid rocket motors. A single-port, three-port and four-port shape has been created and built using Solidworks software. The goal of this study is to determine how the number of ports and the oxidizer pressure affect the hybrid rocket motor's regression rate. The performance of the hybrid rocket motor will be represented by this regression rate, which can either increase or decrease. In the lab-scale experiment, the gaseous oxygen is used as the oxidant and paraffin wax as the fuel. The results show that a 200 kPa pressure oxidizer performs better than a 100 kPa, with a difference of 0.0012 m/s at 1 port, 0.0004 m/s at 3 port and 0.0024 m/s at 4 port. The final result demonstrates that four ports at 200 kPa achieved the highest regression rate, which was 0.0073 m/s. On the whole, the results indicate that increasing the number of ports and also oxidizer pressure will improve the regression rate and therefore subsequently increase the performance of the hybrid rocket motor.

Keywords: hybrid rocket motor; multiport geometry; regression rate; hybrid rocket fuel

NOMENCLATURE

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

1. Introduction

Typically, liquid propellant is used as the oxidant while solid propellant is used as the fuel in hybrid rocket motors (HRMs). Hybrid rocket motors have several benefits, one of which is their safety [1]-[4]. In comparison to the rockets powered by liquid or solid fuel, hybrids are less likely to explode or fail catastrophically. This is because, unlike liquid or solid rocket motors, they use solid fuel grains, which cannot burst. Compared to solid rocket motors, hybrid rocket motors provide more controllability [2]-[9]. Precise thrust control is possible by adjusting the oxidizer flow rate to the fuel flow rate. In general, the cost of manufacturing and operating hybrid rocket motors is also lower than that of liquid or solid rocket motors [10]-[14]. This is because they may be produced using less expensive materials and require a smaller number of intricate components. Because of this, HRMs are drawn to the propulsion systems that can be used for a variety of purposes such as spacecraft propulsion systems, launch vehicles and sounding rockets. Nonetheless, HRMs have two clear disadvantages as a result of the characteristics of non-premixed diffusion combustion: the intrinsically low combustion efficiency and regression rate [2, 10, 15]. In HRMs, the fuel regression rate is the speed at which the fuel surface retreats during a burn. Due to the similar specific impulses of the different hydrocarbon fuels burned with a given oxidizer, this quantity has the first-order effects on the configuration (i.e. length and diameter of the combustion chamber) and consequently the performance of the motor [5, 9, 15]. For a single port motor, a high regression fuel will result in a combustion chamber design that is larger in diameter and shorter than a motor that uses a low regression rate fuel [4, 9]. Regression rate data accuracy is essential for comparing propellants, sizing fuel grains, forecasting hybrid motor performance and preventing burn-throughs.

Numerous studies have been carried out in an attempt to address these two issues. According to the results of 15 static firing tests, the fuel regression rate increases as the chamber pressure rises and decreases as the oxidizer port velocity increases. Axial-injection end-burning type fuel grains by high-accuracy three-dimensional printing have been developed in Ref. [2]. Moreover, the results from studies on the effectiveness of HRMs using the paraffin-based solid fuels in Ref. [3] and Ref. [4] have indicated that the fuels can increase the regression rate. This is highlighted in Figure 1 and Figure 2. Furthermore, the experimental result demonstrated that the application of simple cylindrical multiport design reduces the length-to-diameter ratio of the hybrid thruster and also improves rocket combustion performance. In the meantime, a multiport grain used in a hydrogen peroxide hybrid rocket motor is designed in Ref. [16] as depicted in Figure 3. According to the experimental data, as the number of ports increased, the regression rate improved and the O/F ratio fell while the oxygen mass flow rate remained constant.

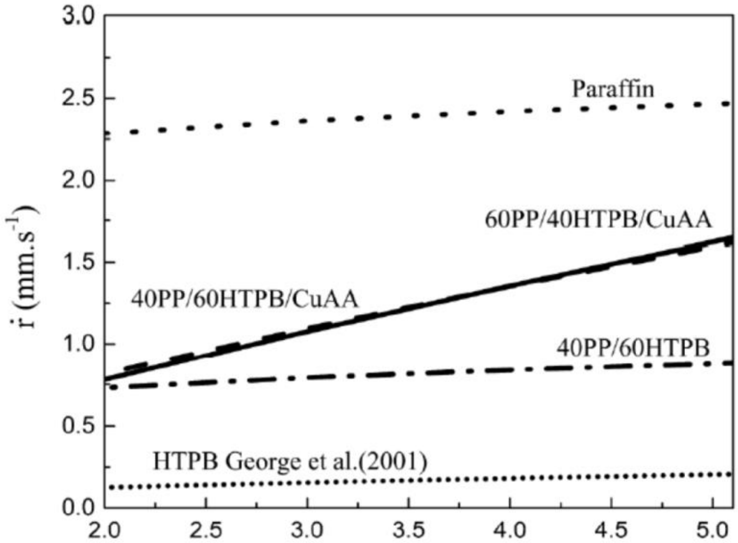


Figure 1: Comparison of regression rates of the four grains [3]

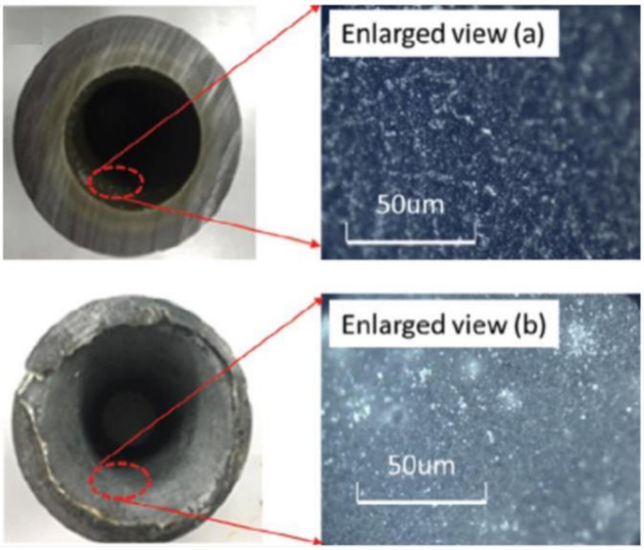


Figure 2: Solid fuel before and after firing test [3]

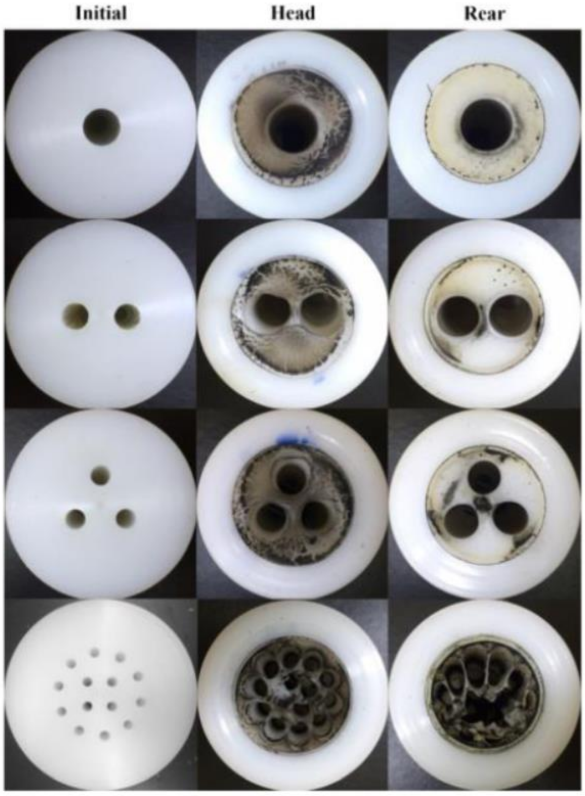


Figure 3: Final ports of the head and back end of the cross-sectional configuration of the HDPE solid fuel grain both before and after the test of hot firing for 1 port, 2 ports, 3 ports and 14 ports [16]

The oxidizer-to-fuel ratio has been shown to be positively shifted to almost its optimal value as the number of ports increases and the increase in the regression rate is reduced beyond four ports [17]. The hybrid rocket motor with multi-port fuel grain has been numerically and experimentally studied in Ref. [8] and Ref. [9]. The findings have demonstrated a relationship between the fuel port profile and flame location and the fuel regression rate distribution. Numerous studies demonstrate that segmented grain design may enhance combustion performance.

Based on findings from previous studies, the purpose of this work is to examine the combustion performance and local regression rate distribution of multi-segmented grains. Furthermore, a thorough analysis is conducted using the numerical simulation results to determine the impact of the segmented grain number and rotation between them, the segmented grain port numbers and the mid-chamber length on the performances. To determine how the grain design affects regression rate and combustion efficiency, aspects of steady flow fields and temperature distributions are examined.

2. Methodology

As indicated, the purpose of this study is to examine how various geometric configurations of the multiport designs affect various mass fluxes on regression rates. To analyze the impact on the regression rate of the hybrid rocket motors, several multiport design geometries were used in conjunction with the fuel and additive preparation. The design specifications have been completely specified, including the parameters to be measured, the cost and the availability of materials. Table 1 tabulates the measurements that were selected to fit the testbed at the IIUM Propulsion Lab. The experiment was conducted using paraffin wax as fuel and oxygen gas as an oxidizer. Furthermore, it has been shown that paraffin wax burns three times faster than regular fuel, achieves substantial thrust and performance, and is much less expensive, non-toxic and also safer than liquid oxygen (GOX). Throughout the experiment, numerous circular ports were used. The fuel requirements listed in Table 1 serve as the indicator. On the other hand, Figure 4 shows how the ports were arranged within the grain, as well as the diameter after firing. The images represent the outcomes of the three cases in this research.

Table 1: Experimental fuel specification

Specification	Fuel Casing (Aluminium)	Fuel		
		1-Port	3-Port	4-Port
Length (mm)	300	280	280	280
Outer diameter (mm)	101.6	95.6	95.6	95.6
Average mass (kg)	0.827	2.440	2.307	2.233

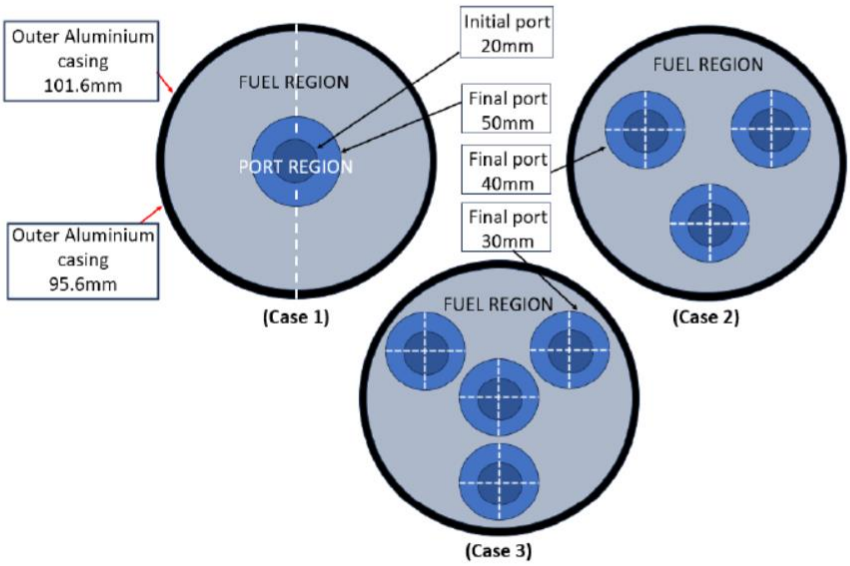


Figure 4: Port configuration and the diameter of the port grain after

Figure 5 illustrates the set-up of the hybrid rocket together with the placements each sensor. In the meantime, a schematic diagram illustrating the connections of every component in the hybrid rocket motor testbed is shown in Figure 6.

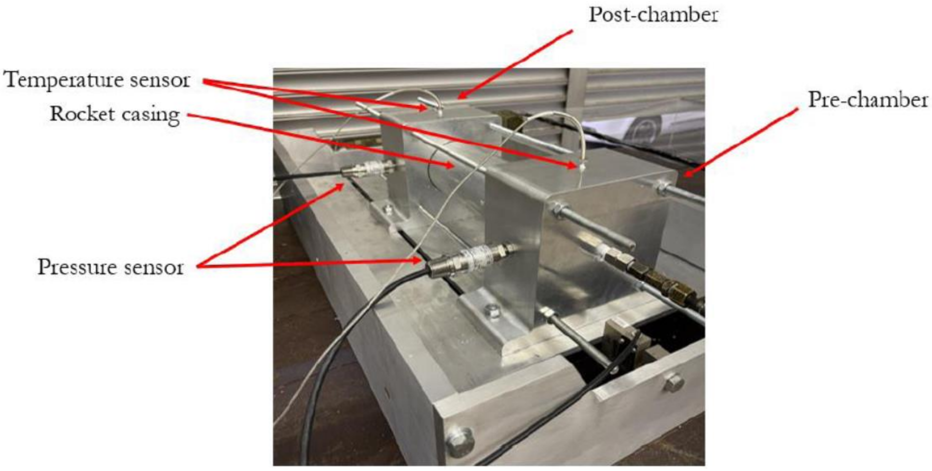


Figure 5: Experiment set up for this study

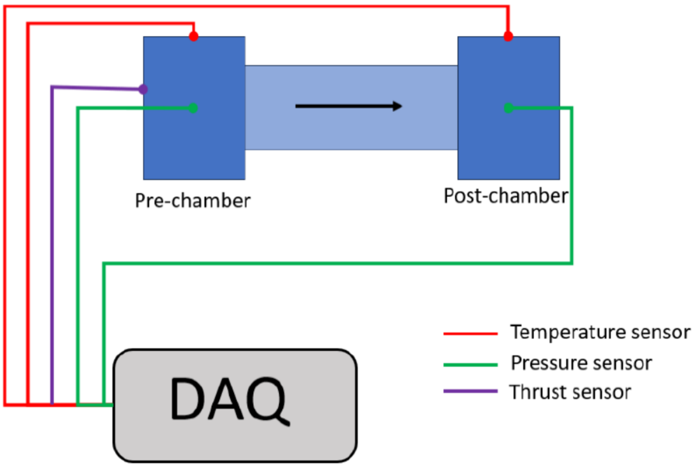


Figure 6: Schematic diagram of the HRM

On the other hand, Figure 7 depicts the feeding mechanism. The oxidizer is gaseous oxygen under self-pressurization without compressor. The following components were included: (1) gaseous oxygen (GOX) tank; (2) main tank cutoff valve; (3) GOX tank pressure gauge; (4) GOX supply pressure regulator; (5) GOX supply pressure gauge; (6) ball valve and (7) motor rocket with a feeding line, port, and convergent-divergent nozzle. Regarding the multiport, the feeding mechanism that was used only modified the fuel in the grain using either 3 or 4 ports.

A tube, hose, steel reducer, steel join, solenoid valve, ball valve and self-pressurized oxygen gas tank served as the feed system. A 10L GOX tank was used as the oxidizer since it was easy to operate and did not require injectors. Another reason is that it is easier to replenish and widely accessible on the market than other oxidizers. Just a basic match makes up the igniting mechanism. The matches were wrapped in a steel wool thread and fastened to a nichrome wire. The wires link the steel wool to a battery supply. Applying a current causes the steel wool to burn, which is followed by lighting the match at the end of the fuel. In Figure 8, the circuit is shown.

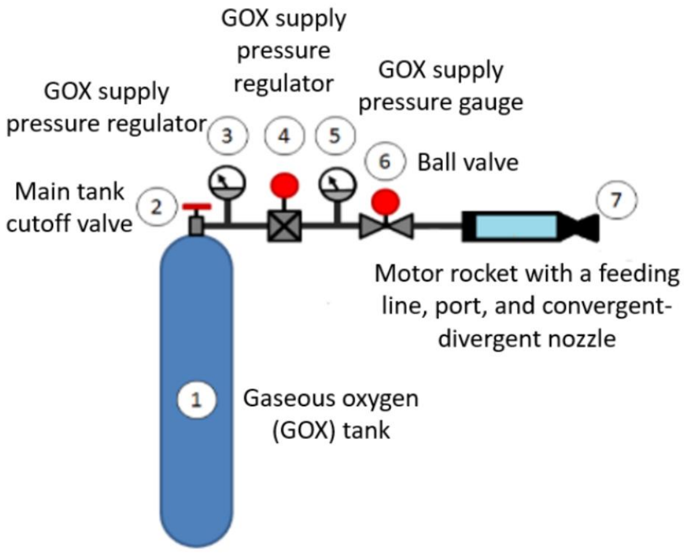


Figure 7: Feeding system

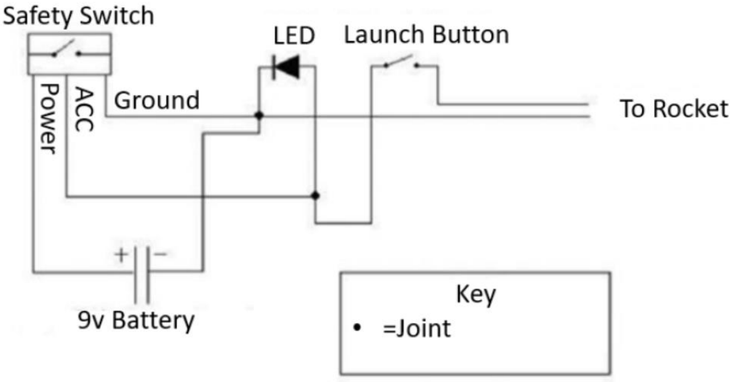


Figure 8: Ignition controller circuit

Regression rate, thrust and exit velocity are examples of performance metrics that were calculated using the relationships given in the following equations. Several crucial parameters such as temperature (in K) and pressure (in kPa) were entered into the formula after the experiment to determine the velocity exit, thrust and regression rate.

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

$$\dot{m}_{prop} = \frac{m_{after} - m_{before}}{t_b} \tag{2}$$

$$F = \dot{m}_{\text{prop}} V_{\text{exit}} + (\rho_{\text{exit}} - \rho_{\text{atm}})A \tag{3}$$

$$I_{\text{sp}} = \frac{F}{\dot{m}_{ox} g_o} \tag{4}$$

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

$$\dot{r} = \frac{r_{\text{after}} - r_{\text{before}}}{t_b} \tag{6}$$

3. Results and Discussion

Three distinct cases were divided up in this study. Two different pressure oxidizers were used for each type of port. Theoretically, the oxidizer-to-fuel ratio would rise along with the input pressure such that it would result in the increase of the HRM regression rate. This investigation was carried out using 200 kPa and 100 kPa. Table 2 illustrates the radius change results for each pressure oxidizer of all three cases.

Table 2: Experimental results data

Case	Pressure Oxidizer (kPa)	Burn Time (s)	Radius Port Before (m)	Radius Port After (m)
1	100	23	0.02	0.05
	200	12	0.02	0.05
2	100	26	0.02	0.04
	200	19	0.02	0.04
3	100	9	0.02	0.03
	200	3	0.02	0.03

The regression rate of the HRM can be obtained from Table 2 by applying the change in the radius divide with the burn time. Note that during each firing process, the fuel was never burned completely since the port changes before and after had to be analyzed. The outcome is tabulated in Table 3 after applying previous Equation 1 to Equation 6. These tables show the HRM's performance as well as the regression rate from various pressure oxidizers and ports.

Table 3: Calculated results from the experimental data

Case	Mass Flux (G_0)	Mass Flow Rate (kg/s)	Thrust, F (N)	Exit Velocity, V_e (m/s)	Regression Rate (m/s)
1	61.54	0.01	149.47	557.66	0.0011
	531.05	0.03	110.68	510.12	0.0023
2	20.51	0.04	93.90	604.31	0.0024
	177.02	0.04	198.32	693.16	0.0030
3	15.38	0.03	156.48	750.61	0.0049
	134.53	0.04	109.37	493.15	0.0073

According to the outcome, case 3 at 200 kPa achieved the maximum regression, which was 0.0073 m/s. The burning area in the grain will rise as the number of ports increases, which will also boost the HRM's combustion efficiency. Theoretically, as the pressure inlet increases, the HRM's velocity exit should go up as well. However, because the fuel wall between the cores collapsed and became one large core, case 3's velocity exit was only achieved at 493.15 m/s at 200 kPa. Figure 9 and Figure 10 illustrate the outcomes of the static firing. It is obvious that when the number of ports increases, a larger flame is produced as a result of the more fuel burn in port grain.

Figure 9: Single port with oxidizer pressure of 100 kPa

Figure 10: Four port with oxidizer pressure of 100 kPa

Furthermore, based on the regression rate result in Table 3, a bar graph is generated and displayed in Figure 11. Regression rate is chosen since it represents a critical issue that the HRM has encountered. According to the three cases, it can be seen that in both pressure oxidizers, four ports have significantly higher capacity than one port and 3 ports. Regression rate is increased from 0.0011 m/s to 0.0023 m/s for a single port as the pressure oxidizer changes. In the meantime, the pressure oxidizer changes only slightly for 3 ports. This indicates that increasing the pressure oxidizer does not greatly enhance the regression rate if there is no core at the center, such as port 3. The regression rate is largest at port 4, where it is 0.0049 m/s at 100 kPa and 0.0073 m/s at 200 kPa. Fuel results before and after the firing operation are displayed in Figure 12.

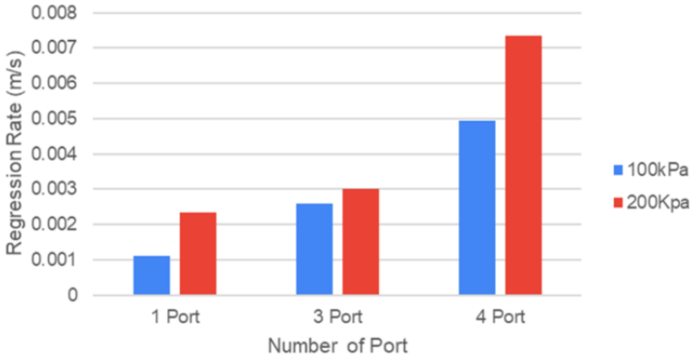
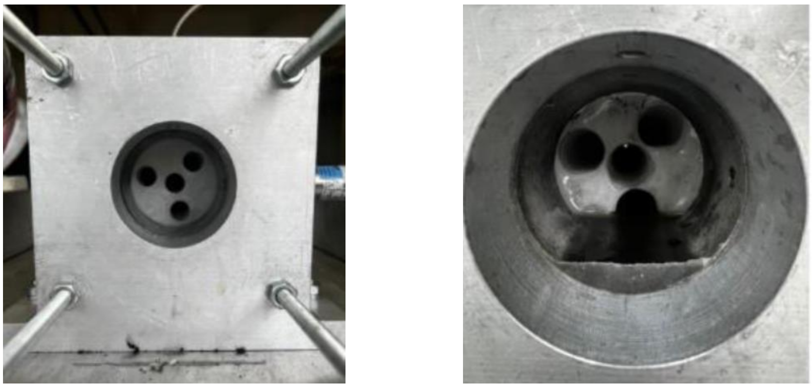


Figure 11: Regression of three types of port with various pressure oxidizer



(a) Before firing (b) After firing

Figure 12: Four ports at 100 kPa

4. Conclusion

A few techniques for increasing the fuel's regression rate are the main subject of this study. While there exist other alternative methods, the primary focus of this paper is on the experimental multiport design with variable mass flux. A lab-scale hybrid rocket test facility has been successfully constructed using accessible components. Some conclusions can be drawn based on the obtained results:

- The fuel grain's geometry can enhance the regression rate by using numerous circular ports.
- The transient performance of the hybrid rocket can be greatly influenced by preliminary designs, starting mass flux, and number of ports used.
- The selection of oxidizers and fuels is a crucial factor in attaining enhanced performance, in addition to its thermochemical characteristics.

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