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Experimental Investigation of Fuel Composition and Mix-Enhancer Effects on the Performance of Paraffin-Based Hybrid Rocket Motors

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Abstract:

Experimental investigations have been performed for a lab-scale hybrid rocket motor with hydrogen peroxide and paraffin-based propellants. A new paraffin-based solid fuel with favorable mechanical strength, consisting of 50 wt% paraffin, 20 wt% PE wax, 18 wt% EVA, 10 wt% SA and 2 wt% carbon, was proposed. The thermal properties of the proposed paraffin-based fuel and its components were firstly evaluated using TG/DTG measurements. It was found that the decomposition rates of each of the components of this paraffin-based fuel follow the order SA > pure paraffin > paraffin-based fuel blends > PE > EVA. Measurements of the regression rate of this paraffin-based fuel were performed and compared with results found in the literature. This showed that the regression rate of this paraffin-based fuel is much higher than that of traditional polymer solid fuels such as HTPB fuels. Finally, by adding a protrusion, a cavity and swirl blades at the end and in the middle of the combustion chamber, experimental investigations into the effects of a mix-enhancer on the paraffin-based hybrid rocket motor were performed. These investigations are discussed in detail.

Keywords: Hybrid rocket motor, Hydrogen peroxide, Paraffin-based, Regression rate

1. Introduction

A hybrid rocket motor (HRM) refers to a rocket propulsion system that uses both a solid and a liquid as propellants. HRMs have multiple advantages compared to solid and liquid rocket motors: they offer high safety in propellant production, storage, transportation and testing processes due to the separately stored oxidizer and fuel [1-4]. Moreover, by regulating the flow rate of oxidizer, variation in the mixture ratio can easily be achieved, and shutdown or restart is possible by closing or opening the oxidizer valve. HRMs can offer a higher specific impulse and thus greater payload capability compared to a solid rocket motor. In addition, the HRM has only half the pipework system required for a liquid rocket motor, and therefore the cost and complexity of the system can be greatly reduced [5]. However, although long known, this type of propulsion has never drawn much interest in the past, partially due to its low regression rate with polymer fuels commonly used as combustibles, such as HTPB (hydroxyl-terminated polybutadiene), etc., and its low combustion efficiency caused by the intrinsic combustion property that combustion occurs only in the turbulence boundary layer as a diffusion flame [6].

Due to the low regression rate of traditional polymer solid fuels used in hybrid rocket motors, for high thrust levels fuel grains with multiple ports are necessary, which results in a low volumetric efficiency [7, 8]. As well as using the multiple-ports structure, various investigations have been performed to increase the regression rate of hybrid rocket motors. It has been found that using a paraffin-based hybrid rocket motor is a possible alternative for higher-thrust hybrid rocket motor applications [1, 5, 9-13]. Paraffin-based fuel (liquefiable fuel) has the advantage of a high regression rate due to its low melting point. It is found that paraffin-based fuel has a regression rate three to five times higher than conventional fuels [9, 14, 15]. In contrast to HTPB, the solid fuel is vaporized directly during the combustion processes. In the case of paraffin-based fuel, a melt layer is formed on the surface of the fuel grain and liquid droplets are entrained via Kelvin-Helmholtz instability [4]. The liquid droplets are entrained by the high-velocity gas flow and mixed with the oxidizer flow. Therefore, the high regression rate of paraffin-based fuel is a result of both fuel vaporization and flow entrainment [16]. Numerous experimental investigations into paraffin-based hybrid rocket motors have been undertaken, including regression-rate measurements, fuel property investigations and a recently increased number of investigations into combustion process visualization [5, 9-12, 17, 18]. However, a review of the literature reveals that most of the previous work with paraffin-based fuels used pure paraffin or paraffin simply mixed with HTPB and polyethylene wax which both have poor mechanical strength and cannot meet the requirements of practical applications. For instance, Kim et al. used fuel blends prepared with pure paraffin and PE wax to visualize the droplet entrainment mechanism[11]. P. Cardoso et al. investigated preparation of paraffin-based solid fuel by formulating paraffin particles within a hydroxyl-terminated polybutadiene binder[17]. Piscitelli et al. assessed and optimized the manufacturing processing of paraffin wax solid fuel[18]. In practical applications, additive components are needed to modify the mechanical properties of paraffin-based solid fuels, to avoid surface and internal rips, defects, micro cracks and other microstructural discontinuities [13, 19]. Investigations into the effects of fuel composition on the performance of paraffin-based hybrid motors are still limited. In the present work, a new paraffin-based solid fuel consisting of hardener, tackifier, plasticizer and carbon, potentially satisfying the mechanical strength requirement in practical applications, is proposed. A lab-scale hybrid rocket motor using hydrogen peroxide as oxidizer has been used to perform firing tests with paraffin-based fuels containing different additive components.

Another open issue related to hybrid rocket motors is combustion efficiency enhancement. Compared to solid or liquid rocket motors, HRMs have lower combustion efficiency due to the intrinsic property that combustion occurs only in the boundary layer, leading to the formation of a detached flame region over the solid combustible surface [4]. Consequently, hybrid rocket combustion is commonly incomplete if no specific device is used to enhance the mixing of fuel and oxidizer. A common approach is to use a mixer at the end of the fuel grain combined with a post-combustion chamber. Another possibility is to place a mixer, such as a bluff body, protrusion or diaphragm, in the first part or in the middle of the fuel grain, to ensure the area after the mixer has better mixing of oxidizer and fuel. Previous numerical investigations have been performed to assess the effects of swirl injections [20] or of adding a diaphragm [21], protrusion [22] or bluff body [23] in the combustion chamber, on the combustion efficiency of hybrid rocket motors. Previous studies were mainly focused on numerical investigations and mostly used traditional polymer solid fuels such as HTPB. Experimental investigations and comparisons of mixing performance among different mix-enhancers such as using a bluff body or diaphragm or changing the combustion chamber length of paraffin-based hybrid rocket motors are still limited. Therefore, the second objective of the present work is to experimentally investigate and compare the effects of post-combustion chamber length on the fuel/oxidizer mixing performance by adding a cavity, a protrusion and swirl blades in the middle and at the end of the fuel grain, and consequently to investigate their influence on the combustion performance of paraffin-based hybrid rocket motors.

The objective of the present work is therefore twofold. Firstly, a new paraffin-based fuel consisting of pure paraffin, hardener, tackifier, plasticizer and carbon is proposed and evaluated by considering the trade-off between achieving favorable mechanical strength to meet the requirements of practical applications and retaining the advantage of a high regression rate. Thermogravimetric and derivative thermogravimetric analyses were also performed for each component and paraffin-based fuel blend, to evaluate their thermal properties. Firing tests were then conducted with different compositions of paraffin-based fuel grains, using a lab-scale hybrid rocket motor with hydrogen peroxide as oxidizer. The regression rate of the proposed paraffin-based solid fuel in the present work will be measured and compared with results from the literature. Finally, the effects of post-combustion chamber length and adding a mix-enhancer (protrusion, cavity or swirl blade) on the combustion performance of paraffin-based hybrid rocket motors will be investigated and discussed in detail.

2. Fuel Grain Preparation

It is well known that paraffin-based solid fuels have the advantage of a higher regression rate than conventional polymer solid fuels such as HTPB-based fuels, but pure paraffin fuels have poor mechanical strength and usually cannot meet the requirements for practical applications. Additives are necessary to improve the mechanical strength. However, additives usually have a lower regression rate and poor combustion properties. The type and quantity of additives should be carefully chosen by considering the trade-off between retaining the high regression rate of the paraffin-based fuel and satisfying the mechanical strength requirement. In the current work, additives, i.e., polyethylene wax (PE), hardener (stearic acid (SA)), binder (ethylene vinyl acetate (EVA)) and toner (carbon powder) have been added to pure paraffin fuels to improve the mechanical strength.

The pure paraffin fuel (paraffin 58) used in the present work was supplied by the Sinopec Group with a melting point of around 58°C. The polyethylene wax (PE) is used because it has better mechanical strength and thermal stability than pure paraffin fuels. EVA acts as wax reinforcement among the different components because of its high cohesive strength and good adhesion properties. Stearic acid is used for better mechanical properties for paraffin waxes and better dipping properties for wax, mainly with a steel combustion chamber. The role of carbon black is to improve the radiation absorption of the fuel, ensuring that most of the radiation from the flame is absorbed at the fuel surface, to avoid sloughing of the solid fuel [24, 25]. A summary of the physical properties of these additives is given in ***Table 1***.

Properties	Paraffin	PE wax	EVA	SA
CxHy	$C_{32}H_{66}$	$(C_2H_4)_{46\sim100}$	$(C_2H_4)_x(C_4H_6O)_y$	$C_{18}H_{36}O_2$
Melting point (K)	331.45	389	346.45	342.15
Density (g/cm^3)	0.92	1.02	1.23	0.91
Calorific Capacity (MJ/kg)	47.36	47.16	40.63	40.60

Table 1: Physical properties of paraffin-based fuel components[24]

No.	Paraffin	PE wax	EVA	Carbon	SA
1	50 %	20 %	18 %	2 %	10 %
2	20 %	50 %	18 %	2 %	10 %
3	0 %	70 %	18 %	2 %	10 %

Table 2: Solid propellants with different ingredient proportions

The aforementioned mixtures, consisting of pure paraffin, PE wax, SA, EVA and carbon powder, were preheated to 433 K and held for 30 minutes (min.), ensuring that all the components were well melted and mixed to obtain a homogeneous and delicate mixture. The melted mixtures were then cast using a high-speed rotating machine. In the present work, three types of paraffin-based fuels with different compositions giving good mechanical strength have been tested with a lab-scale hybrid rocket motor. The composition details of these three solid fuels are listed in ***Table 2.***

3. Experimental Setup

The experiments were conducted using a lab-scale hybrid rocket motor with paraffin-based fuel and hydrogen peroxide (90 wt %) as propellants. As illustrated in ***Figure 1*****,** the whole test facility consists of three major parts: pipework, controls and instrumentation. In the pipework, two fluids are used, i.e., hydrogen peroxide serving as the oxidizer and N_2. A series of valves, a storage tank and various handling components have the purpose of delivering the H_2O_2 to the combustion chamber. N_2 has multiple uses: its primary purpose is to pressurize the hydrogen peroxide tank, but it also serves as a combustion chamber purge, quenching the combustion after a test or in the event of a test abort. Finally, it is used to actuate all the ball valves in the pipework system. For safety purposes, the H_2O_2 tank and delivery lines are connected to a water tank. If leakage or spill occurs, the water will dilute the H_2O_2 quickly to a harmless concentration. The whole system is controlled remotely and experimental data, including the pressure and thrust, are acquired using LabVIEW software. The data acquisition frequency is regulated to 100 Hz.

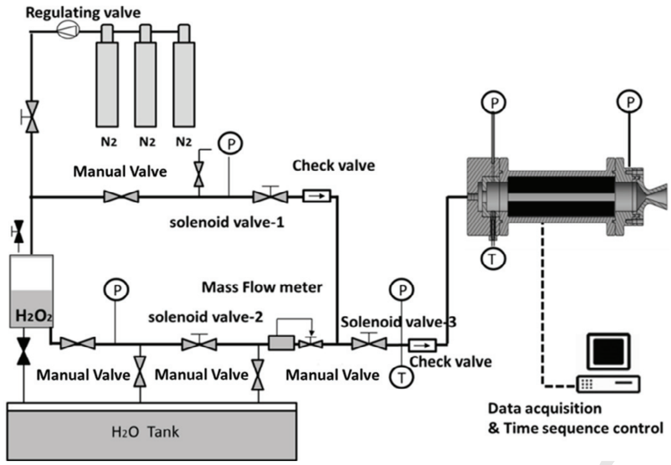

Figure 1: Schematic of experimental setup for the lab-scale hybrid rocket motor

Figure 2 shows the experimental hybrid rocket motor configuration. With a catalytic bed at the head (internal multilayered silver grid) [26], the length of the main combustion chamber of the hybrid rocket motor used in the current work is 240 mm; the lengths of the fore and aft ends of the combustion chamber are 20 and 40 mm respectively. The outer diameter of the solid fuel grain is 70 mm. The hydrogen peroxide flow rate was controlled at 43 g/s, so that the total flow rate with the paraffin-based fuel was around 50 g/s. A conical nozzle made of red copper with a diameter of 5.5 mm was used in the present work. Four pressure sensors were located before and after the catalytic bed at the fore and aft ends of the combustion chamber, to monitor the pressure variation during the firing test.

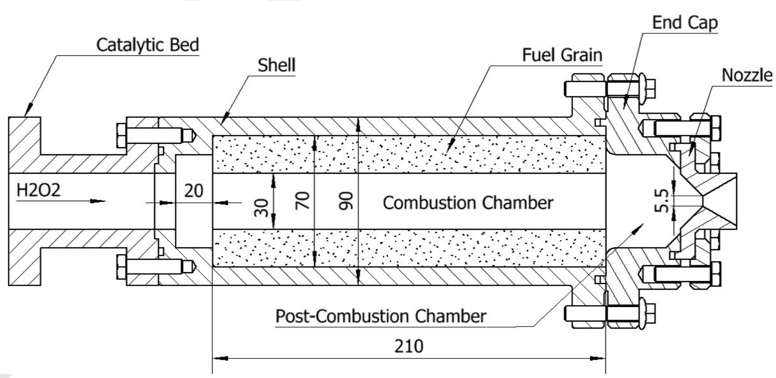

Figure 2: H_2O_2/paraffin-based solid-liquid mixed rocket engine test pipework system

The sequential control of the system is achieved by controlling a series of pneumatic valves located in the feeding line (***Figure 1***). In the present work, the hydrogen peroxide injection time is controlled to between 3 s and 10 s. ***Table 3*** shows an example of sequential control parameters for a burning time of 5 s.

Serial number	Time (s)	Name of action
1	0.0	Data acquisition on
2	5.0	H_2O_2 outlet valve 2 open
3	10.0	Catalytic bed inlet valve 3 open
4	15.0	H_2O_2 outlet valve 2 closed
5	18.0	N_2 purge valve 1 open
6	20.0	N_2 purge valve 1 closed
7	21.0	Catalytic bed inlet valve 3 closed
8	25.0	Data collection off

Table 3: Ground ignition test system timing control

4. Results and Discussion

In order to investigate the effect of additives on the performance of a hybrid rocket motor, firing experiments were firstly conducted with three types of solid fuel grains consisting of various components, as listed in ***Table 2***. Paraffin-based fuel 1, consisting of 50 wt% paraffin, 20 wt% PE wax, 18 wt% EVA, 10 wt% SA and 2 wt% carbon, was used to characterize the regression rate of the proposed paraffin-based fuel. More than 30 firing tests were conducted in total. All tests achieved successful ignition. Reignition tests were also performed with a time interval of 10-30 s, by closing and reopening the oxidizer valves. It was observed that for both the ignition and the reignition tests, a high-pressure combustion regime can be quickly established after opening the oxidizer valve and no obvious combustion instability was observed. Finally, in order to investigate the mix-enhancer effects on the performance of the hybrid rocket motor, firing tests were performed with three different geometries of combustion chamber. The details of the experimental results analysis will be given in the following sections.

4.1 Comparison of Different Fuel Grains

The fuel grains are manufactured using casting machines and it was observed that the additives EVA, PE and SA can effectively improve the mechanical strength of the solid fuel. All the three paraffin-based fuels with compositions as listed in ***Table 2*** can solidify to form a fuel grain with a smooth surface, both inside and outside, and with favorable mechanical strength.

Figure 3 shows the fuel grain before and after the firing test. No obvious external and internal surface rips and defects were observed. An electron microscope (Zeiss Axioskop 40) was used to assess the microcracks of the fuel grain. As shown in ***Figure 3***, the different compositions are homogenously distributed. To further understand the influence of composition on the performance of the solid fuel, the thermal properties of these components and mixtures were examined via thermogravimetric and derivative thermogravimetric analysis experiments (NETZSCH STA 449 F3 Jupiter). The experiments were conducted at a heating rate of 20 K/min. under nitrogen atmospheric pressure conditions with a temperature range of 20-600°C. It is observed that up to 80% by weight of all the components are decomposed at temperatures between 160°C and 300°C, as shown in ***Figure 4***. The decomposition rate is observed to follow the order SA > pure paraffin > mixture > PE > EVA. Moreover, EVA has a much higher decomposition temperature compared to the other components, indicating that less EVA is appropriate for greater reactivity of the fuel mixtures. The DTG plot shows the same trend as the TG variation.

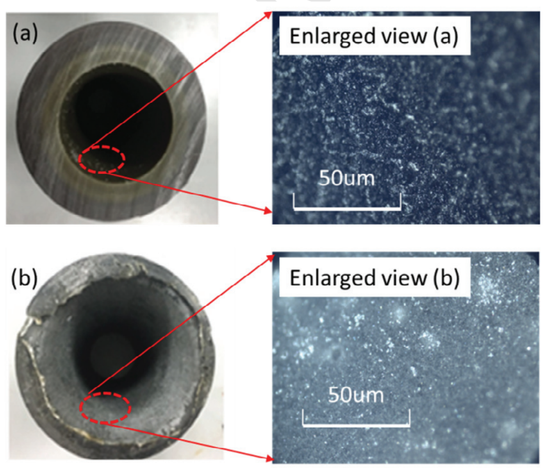

Figure 3: Solid fuel before and after firing test and image with electron microscope: (a) fuel grain before firing test, (b) fuel grain after firing test

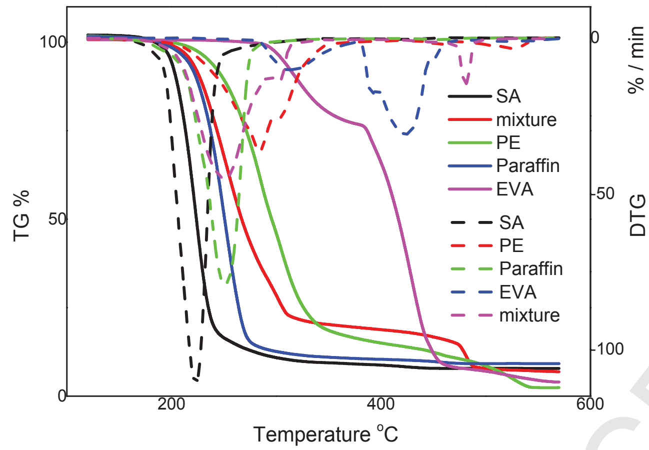

Figure 4: TG and DTG plot of EVA, SA, paraffin and paraffin-based fuel blends

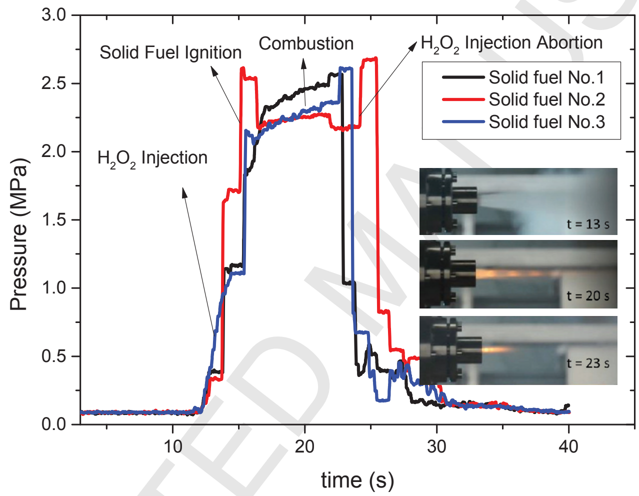

Figure 5: Combustion chamber pressure plot for paraffin-based fuels 1, 2 and 3

Figure 5 shows the pressure variation in the hybrid rocket motor combustion chamber during the firing test for the three paraffin-based fuels. It can be seen from ***Figure 5*** that a quick pressure increase was established due to the H_2O_2 decomposition; after a short ignition of around less than 2 s, the paraffin-solid fuel was successfully ignited. Then, a stable high-pressure combustion regime was established until the shutdown of the oxidizer supply. Moreover, the figure shows that with same flow rate of fuel and oxidizer, solid fuel 1 has a higher value of pressure, indicating that fuel 1 has better performance compared to the other two fuels. Considering the better performance of this solid fuel, investigations into the regression-rate measurement and the effects of a mix-enhancer on the performance of the paraffin-based hybrid rocket motor were undertaken with paraffin-based fuel 1 in the following sections, i.e., fuel consisting of 50 wt% paraffin, 20 wt% PE wax, 18 wt% EVA, 10 wt% SA and 2 wt% carbon powder.

4.2 Regression-Rate Measurement

The fuel regression rate is a key parameter which will directly affect the internal ballistics of the hybrid rocket motor. The regression rate of a solid fuel in a hybrid rocket motor is influenced by the propellant combination, oxidizer mass flow rates, fuel types and fuel components. For a hybrid rocket motor, the regression rate is usually assumed to be governed by the oxidizer flux. This assumption is widely used in experimental research due to its simple expression [27-30]. In order to characterize the regression-rate properties of the new paraffin-based fuel proposed in the present work, measurements of regression rate were performed.

The typical expression for regression rate $\dot{r} = aG^n$ is used in the present work, where $\dot{r}$ is the regression rate, G is the oxidizer mass flux and a and n are the constant coefficients to be determined by fitting to the experimental data. Since the working time in the present study was short, the measurement methodology used was the average differential weight method [29]. Ten firing tests were conducted using fuel grains with different initial diameters to ensure different initial flux density. The fuel grain was weighed before and after the firing test. As the geometry of the fuel grain is a regular cylinder with measurable inner and outer diameter, the regression rate of the fuel grain can be determined by following expression:

$$\dot{r} = \frac{\overline{D}_{bf} - \overline{D}_{af}}{2 * \Delta t} \qquad Eq.1$$

where $\overline{D}_{bf}$ and $\overline{D}_{af}$ are the average inner diameters of the fuel grains before and after the firing test. The inner diameter is measurable; therefore, the inner diameter after the firing test can be expressed as:

$$\overline{D}_{af} = \sqrt{\left(\frac{4\Delta m}{\rho \pi L}\right) + \overline{D}_{bf}^2} \qquad Eq.2$$

where L is the length of the fuel grain, ρ is the density of the solid fuel and Δm is the weight difference before and after the firing test. It should be noted that Δt is obtained from the pressure plot. It starts from the time when the combustion chamber pressure increases to 90% of the steady value, and ends at the time when the combustion chamber pressure drops to 90% of the steady value after the oxidizer valve is closed [29]. As shown in ***Figure 6***, the regression rates of the paraffin-based fuel proposed in the present work are plotted against oxidizer flux density with lin-log axes and compared to experimental results found in the literature. It can be seen that the paraffin-based fuel used in the current work has a higher regression rate than HTPB/GO_x but has lower values than paraffin/GO_x [12]. This suggests that the paraffin-based fuel used in the present work can potentially meet the requirements for mechanical strength while retaining the property of higher regression rate. Correlation has been proposed with the formula $\dot{r} = aG^n$, where the coefficients a and n obtained from experimental data correlation are 0.279 and 0.732 for the paraffin-based fuel proposed in this work.

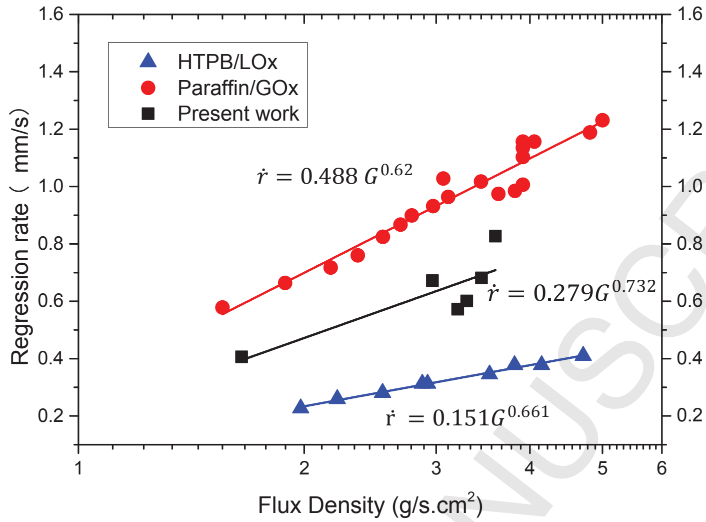

Figure 6: Regression-rate measurement comparison between the paraffin-based fuel proposed in the present work and results from the literature [15]

4.3 Effects of Combustion Chamber Length

The lengths of the combustion and post-combustion chambers are critical to the combustion efficiency and to the stability of the hybrid rocket motor [22, 23]. In this section, in order to clarify the effect of the post-combustion chamber length on the combustion performance of the hybrid rocket motor, experiments were performed with three different lengths of combustion chamber (solid fuel grain lengths): 100 mm, 175 mm and 210 mm, as illustrated in ***Figure** 7*.

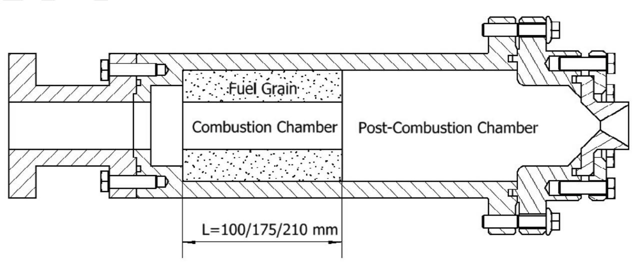

Figure 7*: Schematic of different lengths of combustion chamber*

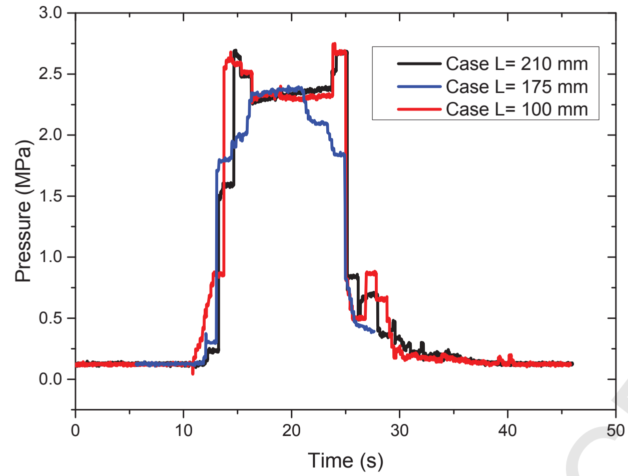

Figure 8: Pressure in combustion chamber with different fuel lengths L = 210, 175 and 100 mm

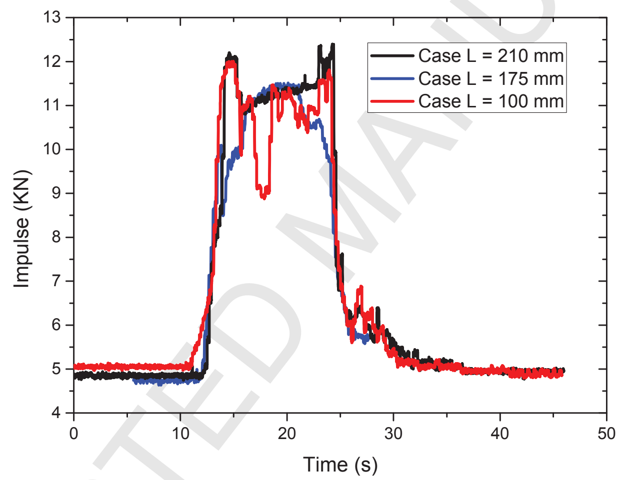

Figure 9: Thrust of hybrid rocket motor with different fuel lengths L = 210, 175 and 100 mm

Combustion chamber pressure and thrust comparisons are plotted in ***Figure 8*** and ***Figure 9.*** It can be seen that even though a combustion chamber length of L=175 mm leads to slightly higher pressure and thrust values, the differences among these three cases remain very small. Throughout the experiments, the average O/F ratios for these three cases were calculated as 3.28, 4.32 and 5.64 (the flow rate of the oxidant was fixed at 43 g/s and the fuel flow rate is obtained by taking into account the weight difference before and after the firing test and the average Δt). It is worth noting that although the thrust remains similar, from the point of view of the specific impulse the case of $L = 100$ mm has a better performance. Because the total flow of oxidant and fuel is reduced, the resulting specific thrust is higher. If the thrust was the same for all three cases, then the rocket can produce the same amount of thrust using a lower mass flow and is thus more mass-efficient.

4.4 Effects of Mix-Enhancer

As previously mentioned, the combustion efficiency in a hybrid rocket motor is generally lower than in a solid or liquid fuel rocket motor, due to the intrinsic property that combustion occurs only in the turbulence boundary layer. A mix-enhancer is necessary to improve the mixing of fuel and oxidizer. In order to investigate the effect of the mix-enhancer on the combustion efficiency of a paraffin-based hybrid rocket motor, experiments were performed in the present work by adding swirl blades, a protrusion and a cavity in the middle or at the end of fuel grains located in the combustion chamber. The details of the dimensions for each case investigated in the present work are given in ***Figure 10***. In order to exclude the effect of the length of the fuel grain and the flow rate of the oxidizer, the fuel grain length was kept at L = 110 mm and the flow rate of oxidizer was kept at 43 g/s for all cases studied. For better comparison among different cases, a reference case without a mix-enhancer with a fuel grain length of 110 mm was also tested (case 1).

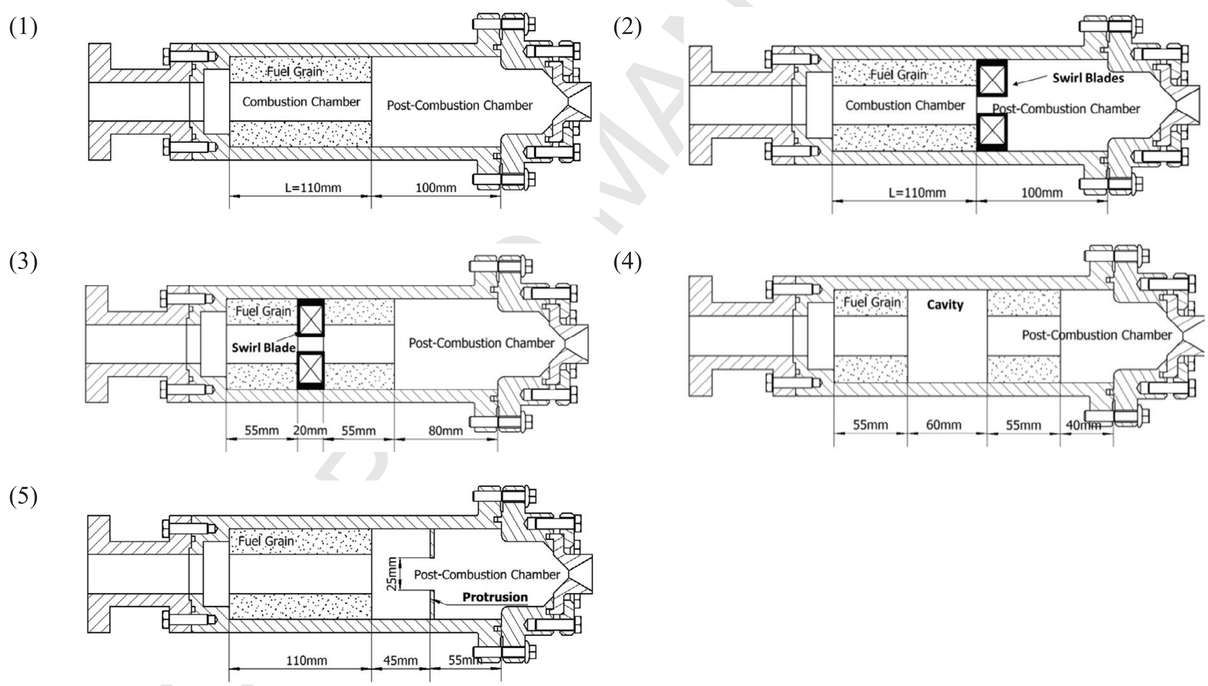

Figure 10*: Schematic of the different mix-enhancer structures investigated in the present work: (1) reference case, (2) swirl blades added at the end of the fuel grain, (3) swirl blades added in the middle of the fuel grain, (4) cavity added in the middle of the fuel grain and (5) protrusion added in the middle of the post-combustion chamber*

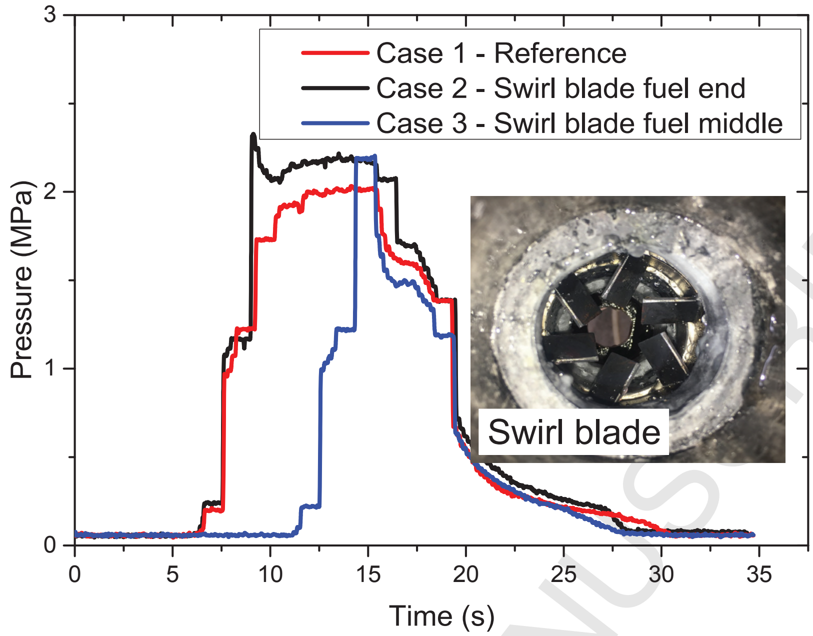

Figure 11: Pressure comparison of cases with and without swirl blades

As shown in ***Figure 11***, in order to investigate the effect of swirl flow on the combustion performance of the hybrid rocket motor, swirl blades, consisting of six blades evenly distributed on the wall of the combustion chamber and inclined to an axial angle of 30°, were added at the end and in the middle of the fuel grain. The comparison between the reference case and the cases with swirl blades is presented in ***Figure 11***. It can be seen that both cases with swirl blades, whether located at the end or in the middle of the fuel grain, have higher combustion pressure than the reference case. The primary consequence of swirl blades added after or in the middle of the fuel grain is that the swirl flow enhances the mixing of the reacting chemical species involved in the combustion process, leading to a more effective burning process, which in turn leads to higher combustion efficiency. It was observed in the present work that the combustion pressure values of cases with swirl blades increased by around 20% compared to the reference case. The results in the present work are in accordance with the numerical investigation of Paccagnella et al. [20]. In their work, the effect of swirl injection on the combustion performance of a hybrid rocket motor was numerically investigated and it was found that swirl injection can effectively improve the combustion efficiency via better mixing of fuel and oxidizer.

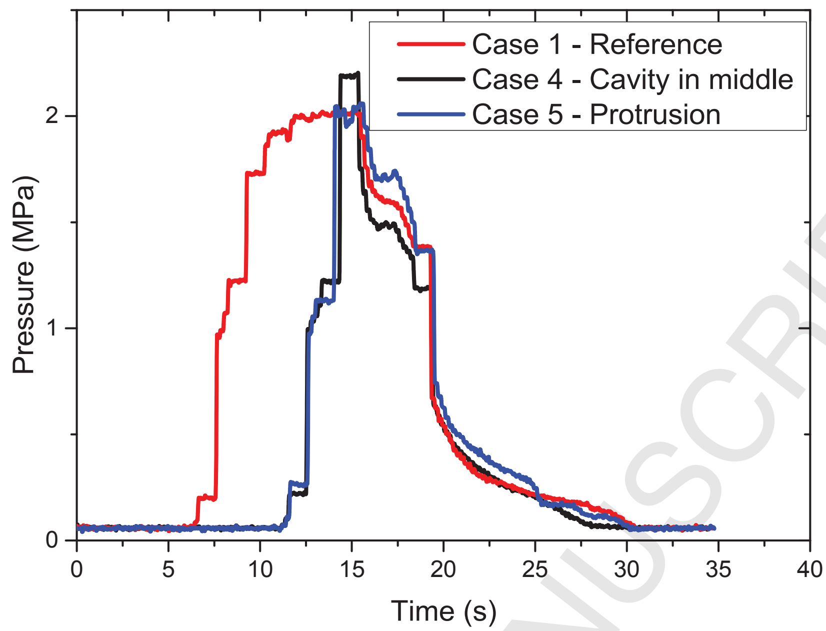

Figure 12: Pressure comparison of cavity added in middle and bluff body added at end.

Comparisons were then made for cases where a cavity was added between two fuel segments (case 4), a protrusion added after the fuel grain (case 5) and the reference case (case 1). As shown in ***Figure 12***, by separating the fuel grain into two parts with a cavity, a higher combustion pressure is obtained, compared to the other two cases. The purpose of adding a cavity between the two parts of the fuel grains is to generate a flow vortex in the combustion chamber and hence to improve the mixing of fuel and oxidizer. The dimension of cavity is chosen with a depth-length ratio of $1<L/D<5$ to ensure a stable recirculation zone can be established in the cavity[31]. It appears that the vortex helps the transport of oxidizer away from the axis to be burnt with the fuel at the interface of the vortex. Therefore, the interaction surface between the fuel and the oxidizer, and hence the combustion efficiency, is increased compared with cases without a large-scale vortex. The results observed in the present work are in accordance with previous numerical results reported in the work of Messineo et al. [32].

It should be noted that adding a protrusion (case 5) does not lead to higher combustion pressure values compared to the reference case. Experiments with a protrusion were repeated several times and the same trend was observed. This differs from the previous numerical investigations of Bellomo et al. [33], although similar results were reported in their experimental work, which showed that adding a protrusion in the combustion chamber led to a pressure drop [34]. A possible reason for the pressure drop is that the position of the diaphragm was not appropriately chosen. As indicated in the work of Kumar et al. [22], the improvement in efficiency depends on the location of the protrusion in the combustion chamber. An explanation can also be found in [33], indicating that the use of a protrusion alone does not result in any significant improvement in either the regression or the combustion efficiency, especially for paraffin-based fuels, because the combustion of paraffin-based fuel is partially dominated by droplet combustion.

5. Conclusion

Experimental investigations into the effects of fuel composition and a mix-enhancer on the combustion performance of a paraffin-based hybrid rocket motor have been performed using a newly proposed paraffin-based fuel consisting of pure paraffin, EVA, SA, PE wax and carbon, with H_2O_2 as the oxidizer. The inferences drawn from the above studies can be summarized as follows.

- From the results of TG/DTG, it is observed that up to 80% of the weight of all components is decomposed between temperatures of 160°C and 300°C. The decomposition rate is observed to follow the order SA > pure paraffin > paraffin-based fuel (blends) > PE > EVA. Moreover, EVA has a much higher decomposition temperature compared to the other components.
- A paraffin-based fuel consisting of 50 wt% paraffin, 20 wt% PE wax, 18 wt% EVA, 10 wt% SA and 2 wt% carbon has favorable properties in terms of mechanical strength and a high regression rate compared to HTPB/H_2O_2 as propellants.
- Adding a mix-enhancer such as a cavity between the two parts of the fuel grains or adding swirl blades in the middle of or after the fuel grain, can effectively improve combustion performance. Adding a protrusion alone does not result in any significant improvement in combustion efficiency.
- Further numerical or combustion visualization diagnostics in the combustion chamber are necessary to understand the physics related to flow patterns, vortex shedding, etc. when a mix-enhancer is added.

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