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Performance Parameter Estimation of Hybrid Rocket with Varying Concentration of Hydrogen Peroxide

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ABSTRACT

Hydrogen peroxide (H_2O_2) is gaining interest as a green oxidizer for rocketry applications due to its non-toxic characteristics and easy availability at a lower cost. This study investigates the combustion efficiency and regression rate of paraffin wax fuel with H_2O_2 as an oxidizer at three concentrations: 50 %, 70 %, and 90 %. Since it also aims to avoid using any catalyst for H_2O_2 decomposition, gaseous oxygen was used to initiate and sustain combustion. Experiments were conducted using a lab-scale hybrid rocket motor to evaluate performance parameters. Results show that ignitability and combustion stability improved with increasing H_2O_2 concentration. The regression rate at 90 % H_2O_2 is 1.93 mm/s higher than at lower concentrations, and the average combustion efficiency improved to 60.2 %, indicating significant enhancement compared to lower concentrations. In contrast, the 50 % H_2O_2 exhibited poor ignition and negligible combustion efficiency due to high water content acting as a flame quencher. Also, the influence of residual oxidizer from prior firings was observed to improve combustion behavior in subsequent tests. The findings confirm that higher H_2O_2 concentrations significantly enhance combustion performance in hybrid systems, providing insights into practical oxidizer selection strategies for green propulsion applications.

Keywords: Hydrogen peroxide; Hybrid rocket; Paraffin wax; Regression rate; Combustion efficiency

NOMENCLATURE

$\dot{r}$	: Regression rate (mm/sec)
d_f	: Final port diameter (*m*)
F	: Thrust (N)
$\dot{m}_f$	: Fuel mass flow rate (g/s)
γ	: Specific heat ratio
L	: Length of fuel grain (*m*)
η	: Combustion efficiency
d_i	: Initial port diameter (*m*)
O/F	: Oxidizer to fuel ratio
A_t	: Nozzle throat area (m^2)
G_{ox}	: Oxidizer mass flux ($g/cm^2.s$)
A_p	: Port area (m^2)
PW	: Paraffin wax
HTPB	: Hydroxyl-terminated polybutadiene
C	: Concentration of solution
V	: Volume of solution (m^3)
LOX	: Liquid oxygen
N_2O_4	: Di-nitrogen Tetroxide
N_2O	: Nitrous oxide
H_2O_2	: Hydrogen Peroxide

1. INTRODUCTION

A hybrid rocket combines the advantages of solid and liquid rocket propulsion syatem, utilizing a combustion chamber containing a solid fuel grain and a liquid or gaseous oxidizer in a separate tank[1]. The solid fuel, typically composed of materials such as paraffin wax, high-density polyethylene etc., offers stability and ease of handling. At the same time, the oxidizer stored in a cryogenic or non-cryogenic liquid form, enables controlled combustion. During the operation, the oxidizer is injected into the combustion chamber through an injector system, where it mixes with the solid fuel grain. To initiate combustion, particularly for non-hypergolic fuel combinations, an igniter is required, mostly a pyrotechnic igniter[2-3]. Once ignited, the combustion process produces hot gases that expand through a converging-diverging nozzle, generating thrust for propulsion.

One of the hybrid rockets' primary safety advantages is their reduced risk of explosion compared to solid rockets. Traditional solid rockets can potentially explode due to their highly energetic propellant and the risk of cracks forming in the grain, leading to sudden increases in burning surface area. Hybrid rockets, by contrast, utilize non-reactive solid fuels paired with separate liquid or gaseous oxidizers, minimizing the likelihood of uncontrolled combustion events. Furthermore, hybrid rockets offer greater thrust controllability compared to solid rockets, enabling precise maneuvering during launch and flight. This controllability stems from the ability to regulate the flow rate of the oxidizer, thereby modulating combustion intensity and thrust output. However, optimizing the combustion process in hybrid rockets presents significant engineering challenges. Achieving efficient mixing and combustion of the fuel and oxidizer requires careful design of the combustion chamber and injector system[4]. Parameters such as fuel grain geometry, oxidizer flow rate, and combustion

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chamber pressure influence combustion dynamics and must be meticulously controlled to maximize performance. The hybrid rocket engine experiences low thrust generation due to a low regression rate during combustion. To improve the regression rate, researchers have used various methods such as the protrusion method[5], the bluff body method[6], and the multi-location swirl injector[7]. These methods increase the regression rate by creating recirculation zones, diverting oxidizer flow, and increasing oxidizer mass flux over the fuel surface. After various experimental research in hybrid propulsion over a few decades, the research worldwide shifted towards exploring motor-using oxidizers that require simple operation.

Hybrid rocket system, particularly those employing hydrogen peroxide (H_2O_2) as the oxidizer, have garnered significant attention in propulsion research due to their potential advantages in safety, controllability, and performance. Hydrogen peroxide was investigated not only for hybrid rocket but also for composite solid propellants[8]. Throughout numerous studies, researchers have explored the use of H_2O_2 in hybrid rockets and gathered valuable data to optimize engine design and operation. Experimental investigations have focused on various aspects of H_2O_2-based hybrid rockets, including fuel-oxidizer compatibility, combustion efficiency, ignition characteristics, and performance metrics. Schmierer[9], *et al.* showed a high performance of 75 KN thrust by using paraffin wax and liquid oxygen combination. Similarly, Gaurav[10], *et al.* found that aluminized wax-based fuel with hydrogen peroxide improves density and specific impulse, achieving the highest specific impulse at an O/F ratio of 1. Pal[11], *et al.* discovered that adding metal additives like aluminum and boron increased the energy density of paraffin-based fuels for hybrid rockets. David[12], *et al.* demonstrated enhanced ignition of solid hydrocarbon fuel through the utilization of a 90 % concentration of hydrogen peroxide. Whitmore[13-14], *et al.* delved into the performance of ABS fuel when combined with H_2O_2 and GOX oxidizers, assessing various motor designs. Notably, studies employing predominantly highly concentrated hydrogen peroxide examined diverse fuel pairings, such as high-density polyethylene by Yun[15-17], *et al.* hydroxyl-terminated polybutadiene by Rajesh[18], *et al.* Additionally, Cassese[19], *et al.* explored PVC performance with H_2O_2 in a small-scale hybrid thruster for satellites, yielding promising results. Meanwhile, Lee[20], *et al.* studied the catalytic decomposition of 90 % H_2O_2 with PE (PolyEthylene) and PMMA (PolyMethyl MethAcrylate) fuels, observing an average chamber pressure rise of 18 bar at approximately 100 g/s oxidizer mass flow rate.

Researchers also conducted numerical investigations[21-22] utilizing 98 % H_2O_2 with HTPB fuel and with the addition of aluminum and aluminum hydride in HTPB[23]. A study by Thoine[24], *et al.* found that using hydrogen peroxide as an oxidizer in a multi-pulsed hybrid rocket engine increased combustion efficiency from 85 % to 91 %. Additionally, integrating a swirl gaseous injector alongside a swirling stream further improved combustion efficiency to 98 %. Kang[25], *et al.* increased the hydrogen peroxide concentration to 95 % and observed improved rocket performance in terms of fuel regression rate, O/F ratio shifting, characteristic velocity effectiveness, and ignition delay. Okninski[26], *et al.* found that using 98 % high-test peroxide (HTP) as an oxidizer and high-density polyethylene (HDPE) fuel in hybrid rocket propulsion is safe and efficient. Their tests showed flights reaching Mach 2.05 and 23 km altitudes, indicating the potential for more efficient space transportation compared to lower HTP concentrations.

Nowadays, environmental concerns are more prominent, and rocket industries are trying to shift towards green propulsion systems. Due to the eco-friendly nature, low cost, and handling simplicity of hydrogen peroxide (H_2O_2), it is being considered as an attractive oxidizer for the future in hybrid rocket applications. Although various literature is available related to the uses of H_2O_2 in a hybrid system, it does not give in-depth information about its ignitability, complexity in handling different concentrations of the H_2O_2, also about the variation in the performance with the change in concentration of H_2O_2 without using any catalyst to decompose it. Apart from this, it has been known that paraffin wax (PW) has a four times higher regression rate than conventional hybrid fuel such as HTPB. Moreover, PW is eco-friendly and easily available at a cheaper rate, making it a promising fuel option for hybrid rockets in the future. Thus, in this paper attempts are made to estimate the performance parameters of varying concentrations of hydrogen peroxide (H_2O_2), in combination with gaseous oxygen (GOX), using paraffin wax as the fuel without employing any catalyst for H_2O_2 decomposition.

Figure 1. Rotatory evaporator used for obtaining rocket grade H_2O_2 from 50 % H_2O_2.

2. EXPERIMENTAL PROCEDURE

2.1 Preparation of High-Concentration Hydrogen Peroxide

Hydrogen peroxide is a transparent and colorless liquid that has a similar appearance to water, but it is denser. It is a potent oxidizing agent that releases water and oxygen as it exothermically decomposes[27]. HTP (High-Test Peroxide), also known as high-concentration hydrogen peroxide (>70 %), is commonly used in rocket applications and for industrial purposes. To achieve high-quality concentration, a 50 % solution is evaporated with the help of a rotary evaporator as shown in Fig. 1. This device is commonly used for solvent distillation under vacuum conditions in scientific experiments. According to Rarata[28]*, et al.*, this method is considered safe for concentrating hydrogen peroxide.

The final concentration of the obtained solution from the evaporator flask is measured by using Eqn. (1) where subscripts 1 and 2 represent the initial and final values respectively of concentration and volume[29].

$$C_1V_1 = C_2V_2 \tag{1}$$

A hydrogen peroxide solution was obtained with 70 % and 90 % concentrations. To verify the accuracy of the concentrations, a refractometer was utilized. This device measures the amount of water in a solution by determining the refractive index of the liquid, which can vary depending on the moisture content[30]. The refractive index and the specific gravity of each obtained concentration were measured with an uncertainty of 0.08 % and 1.07 % respectively, and values are shown in Table 1. The concentration versus measured refractive index relationship has been validated by the existing literature[30].

Table 1. Refractive index and specific gravity of H_2O_2

H_2O_2 concentration (%)	Refractive index	Specific gravity
50	1.36	1.200
70	1.38	1.289
90	1.40	1.399

2.2 Preparation of Fuel Grain

Paraffin wax (PW) was used as the fuel. A solid fuel grain with an annular center port was made using a mandrel and a mould, following the procedure adopted by Dinesh[31], *et al.*. To give structural support to the wax grain, a PVC tube was used. The wax was melted using an induction heater set at 100 °C and poured into the mould and mandrel. The wax was left to solidify at room temperature and then removed from the mould, as shown in Fig. 2. The prepared fuel grain's geometrical description is given in Table 2. The fuel density was determined as 910 kg/m³ via the water displacement method, with an uncertainty of around 6 %.

2.3 Experimental Setup

Figure 3 shows a schematic of the plumbing and tankage connected with the test apparatus. Although this arrangement was already in place, it was updated for the use of H_2O_2. This device enables a H_2O_2-based hybrid rocket motor to be safely fired by an electrically operated actuator valve from a concrete-enclosed control room. The entire feed system is made of SS316, which can withstand high concentrations of hydrogen peroxide. A nitrogen cylinder with a manual valve is used to pressurize the high-pressure hydrogen peroxide tank. The mass flow rate of the oxidizer was measured using a weighing machine by knowing the mass of the cylinder before and after the experimentations.

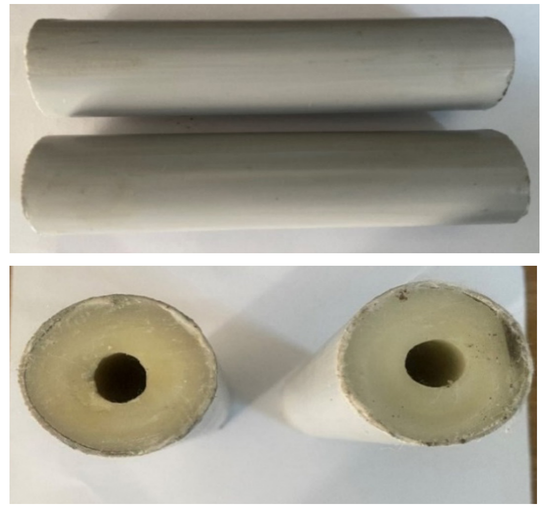


Figure 2. Casted paraffin wax fuel grain in a PVC pipe.

Table 2. Dimension of hybrid rocket motor and fuel grain

Geometrical parameters	Dimensions
Throat diameter, mm	10
Length of the combustion chamber, mm	190
Fuel grain length, mm	190
Initial port diameter, mm	15
Fuel grain outer diameter, mm	46

A solenoid valve controlled the flow of oxygen gas into the combustion chamber, while two sets of actuator valves controlled the flow of hydrogen peroxide. The actuator valves were connected to a control panel from the control room and would activate when a pressure of 10 bar was applied. A sequential timer (Selec, PT-380) with a least count of 0.01 sec. was connected to the solenoid valve, which would automatically disconnect after a predetermined set time. A sequential timer was also connected to a DC power supply, which was used for igniting purposes.

The system depicted in Fig. 3 included various safety measures, such as a manual valve to drain the hydrogen peroxide oxidizer tank in case of emergencies. The instrumentation for these systems included a pressure transducer to monitor chamber pressure and a load cell to measure axial thrust. The UNIK 5000 pressure transducer was used with a pressure range of 0 to 50 bar. To capture the test data, a Windows-based computer with an NI data collection card was used, which required a 12V source to power up the data acquisition systems. Figure 4 shows a schematic diagram of the hybrid rocket motor used for this study.

The combustion chamber is supplied with liquid hydrogen peroxide through four 0.5 mm holes using axial injection, while gaseous oxygen is supplied through four 1 mm holes at a 45^0 angle using swirl injection. The fuel grain was fixed

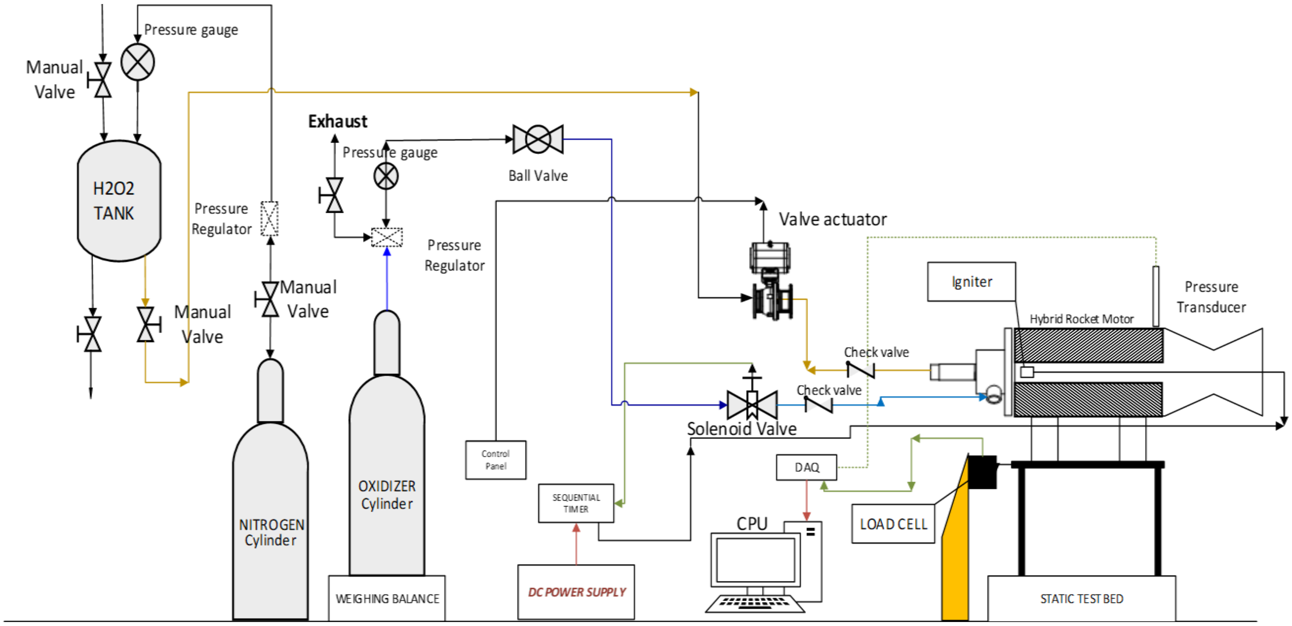


Figure 3. Schematic view of hybrid rockets experimental setup.

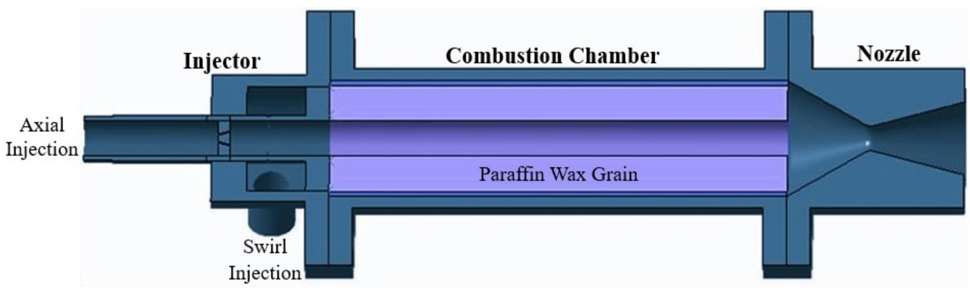


Figure 4. Schematic of hybrid rocket motor used for the present study.

within the combustion chamber casing as shown in Fig. 4. The nozzle with a 10 mm throat diameter and with area ratio of 4 is made up of stainless steel with an inner layer having graphite to withstand the high temperature of the combustion product.

2.4 Estimation of Performance Parameter

In this study, the regression rate was calculated using the weight loss method[32], which involved measuring the weight of the motor after and before combustion every sec. after test firing. It was computed using the known data such as the amount of fuel consumed (Δm), the density of fuel (ρ_f), the initial port diameter (Di), the length of fuel grain (L), and the final diameter (D_f) of grain after combustion. Burn time (t_b) and the oxidizer's mass flow rate ($\dot{m}_{ox}$) were used to compute further regression rates and mass flux respectively.

$$D_f = \sqrt{\frac{4\dot{m}_f}{\pi \rho_f L} + D_i^2} \quad (2)$$

An interrupted test firing of the hybrid rocket motor can be used to compute the final diameter using Eq. (2). The equations (3) to (5) are used to compute the regression rate and the oxidizer mass flux. The oxidizer mass flux (Gox) was calculated using the average of initial and final port areas derived from physical measurements before and after the combustion. Indeed, this approach provides an averaged approximation due to the limitation of direct in-situ measurement. However, this method assumes uniform regression along the grain length, which is a simplification. Thus to have minimum error in averaging, normally burn time was chosen to be smaller as documented[32].

$$\dot{r} = \frac{D_f - D_i}{2t_b} \quad (3)$$

$$A_p = \frac{\pi}{4}\left(\frac{D_f + D_i}{2}\right)^2 \quad (4)$$

$$G_{ox} = \frac{\dot{m}_{ox}}{A_p} \quad (5)$$

For the calculation of combustion efficiency, the experimental C* was calculated using chamber pressure (P_c), throat area (A_t), and mass flow rate ($\dot{m}$). Here, mass flow rate ($\dot{m}$) is total mass flow rate which includes fuel as well as oxidizer.The pressure transducer gives the pressure vs time data for the given burn time.

$$C^*_{exp} = \frac{P_c A_t}{\dot{m}} \quad (6)$$

The combustion efficiency is defined using characteristics velocity (C*), the ratio of experimental and theoretical value.

$$\eta_{c*} = \left(\frac{C^*_{exp}}{C^*_{theo}}\right) * 100 \quad (7)$$

In Eqn. 7, theoretical characteristic velocity was determined using the NASA CEA program[33]. To compute this, the input parameters such as chamber pressure and O/F ratio were taken from the experimental studies. Theoretical variations of C* with varying O/F for wax for H_2O_2, oxygen and its combination is plotted and it is shown in Fig. 5. These theoretical C* are used to get the combustion efficiency. The C* efficiency is used to express the degree of completion of the energy release and the creation of high-temperature, high-pressure gas in the chamber.

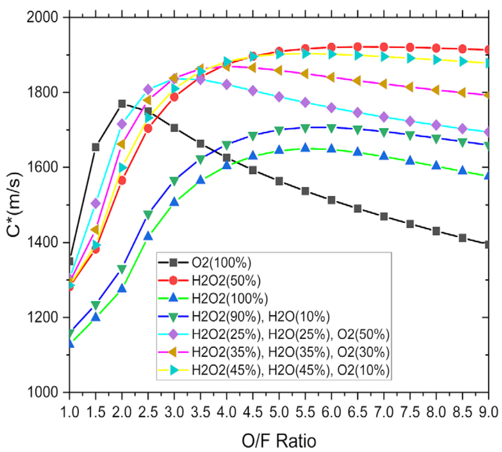


Figure 5. Characteristics velocity obtained from NASA CEA program for different combinations of oxidizer with wax as a function of O/F ratio.

3. RESULTS AND DISCUSSION

3.1 Regression Rate Studies

3.1.1 Experiments with Gaseous Oxygen

A static firing test was conducted using gaseous oxygen as the oxidizer and wax as the fuel, serving as the base case for comparison with hydrogen peroxide testing. The aim was also to assess the impact of swirl flow on regression rate, achieved through firings with both swirl and showerhead injectors. For each case, a total of 4 secs of firing time with an interruption of 1 sec. The weight of the motor was measured before and after every 1sec firing test. The O/F ratio changes with each firing as the oxidizer amount is the same in all firings but the fuel mass flow rate is different in each firing. The oxidizer flow rate was maintained at 24 g/s in the case of the swirl injector while with the showerhead it was 28 g/s.

The oxygen mass flow rate was obtained by knowing the mass difference of the oxygen cylinder before and after the experiments with the known time. The least count of the weighing machine was 1 g and its capacity was 150 kg. The mass flow rate used here is an average value. For the better accuracy of the mass flow rate, prior to experiment mass flow rate was obtained for the total duration of 10 sec, such that accurate flow rate can be obtained with least error. The error involved with the 1 sec mass flow rate was 4.6 %, while its error reduces to 0.5 %, when flow rate obtained by considering the 10 sec. The mass change was observed to varying within a range 27-29 g with the firing time of 1 s.

The regression rate, oxidizer mass flux, and mass index uncertainties are 2.86 %, 9.48 %, and 9.71 % respectively. The power fit curve for both injectors is shown in Fig. 6. The port area of the grain increases after each firing due to which oxidizer mass flux also reduces as it is inversely proportional to the port area. The regression rate drops as the oxidizer mass flux is reduced throughout the combustion process. Due to both the tangential and axial components of the oxidizer flow rate in the swirl injector, the tangential component of the oxidizer provides enhanced oxidizer mass flux over the fuel surface that regresses more and improves heat transfer which results in more regression rate as compared to the showerhead injector.

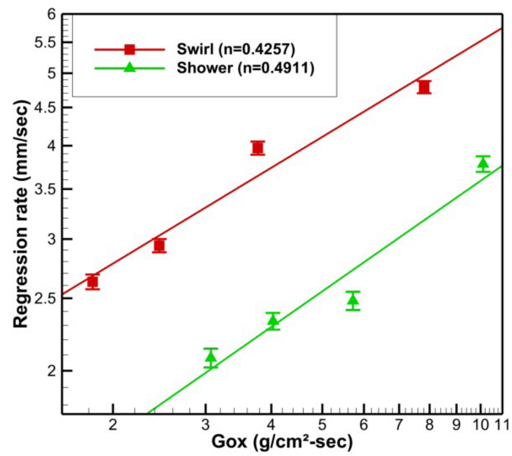


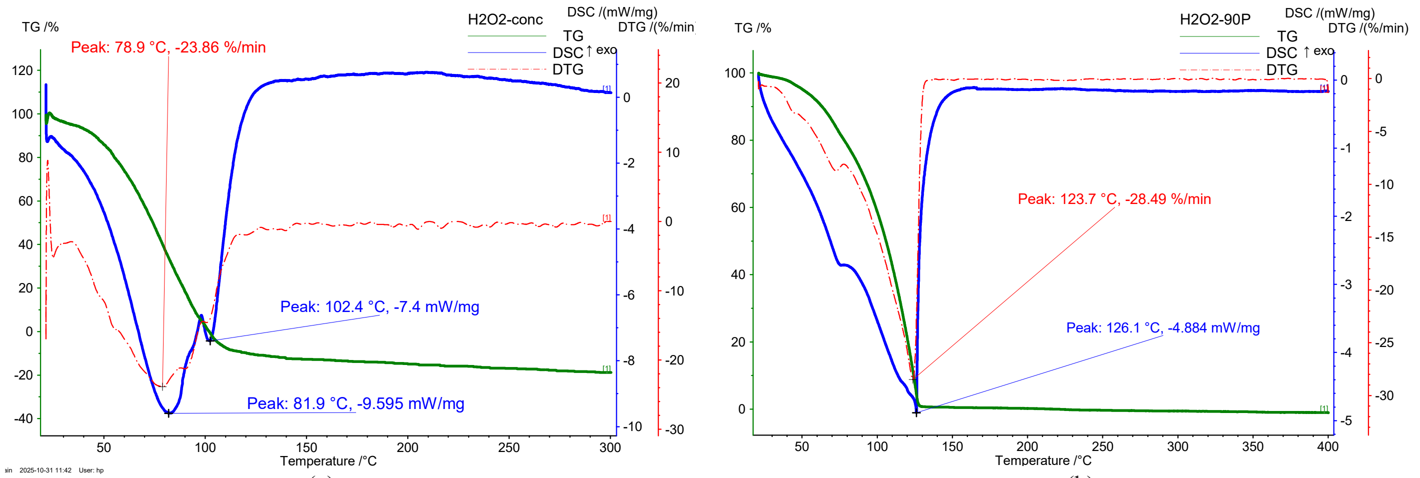
Figure 6. Regression rate vs oxidizer mass flow power fit curve for both swirl and showerhead injector.

3.1.2 Experiments with Hydrogen Peroxide and Gaseous Oxygen Combination

Experimental studies were conducted using hydrogen peroxide (H_2O_2) as an oxidizer and wax as fuel. The H_2O_2 tank was pressured from 10 to 35 bar at varying intervals to determine the mass flow rate of H_2O_2. A weighing scale with an accuracy of 0.001 gram was used to determine the collected H_2O_2 weight difference. The mass flow rate of hydrogen peroxide was calculated experimentally using the injector used for this study. These values were averaged over 5 sec. flows to estimate operational mass rates during firings.

Preliminary findings revealed that H_2O_2, when used alone, has difficulties in sustaining combustion due to the absence of a catalyst bed for its decomposition. The thermal decomposition behavior for 50 % and 90 % H_2O_2 has been obtained in an inert environment of nitrogen as shown in Fig. 7. It is observed from the TGA curve that the decomposition temperature for 50 % H_2O_2 is 102.4 °C and 126.1 °C for 90 % H_2O_2.

To decompose H_2O_2, high heat is required due to the presence of 50 % water concntration. Therefore, gaseous oxygen was used to sustain ignition and provide steady combustion. The injector had two components - axial and swirl. The axial part was connected to the hydrogen peroxide supply while the swirl part was connected to the oxygen supply. The swirl component of oxygen helps to improve the atomization of hydrogen peroxide by supplying gaseous oxygen tangentially. The hydrogen peroxide tank was pressurized with the pressurized nitrogen gas. The experiment was conducted with the combination of hydrogen peroxide and gaseous oxygen in which H_2O_2 was pressurized with nitrogen gas at a pressure of 20 bar and a 20 g/s mass flow rate. The mass flow rate of gaseous oxygen was 8 g/s at 25 bar . The hydrogen peroxide and oxygen gas were injected into the combustion chamber in a 70:30 ratio for each concentration of hydrogen peroxide.



(a) (b)

Figure 7. TGA Curve in an inert environment for (a) 50 % H_2O_2, and (b) 90 % H_2O_2.

Table 3. Regression rate vs Gox with varying concentrations of H_2O_2

Concentration of H_2O_2	Time (s)	$\dot{r}$ (mm/s)	G_{ox} (g/cm².s)	O/F ratio
	4	0.78	10.87	3.16
50 % H_2O_2	4	0.70	6.17	3.03
	4	0.64	4.13	2.73
	3	1.57	9.18	1.65
70 % H_2O_2	3	1.33	4.42	1.35
	3	1.12	2.79	1.27
	2	1.93	10.74	1.50
90 % H_2O_2	2	1.39	5.87	1.54
	2	1.30	4.00	1.36

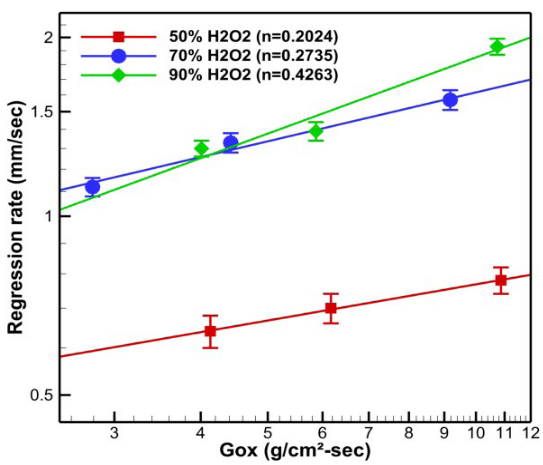


Figure 8. Regression rate v/s oxidizer mass flow power fit curve for 50 %, 70 %, and 90 % H_2O_2.

Three static firings were conducted for each 50 %, 70 %, and 90 % concentrated hydrogen peroxide with a burn time of 4, 3, and 2 secs, respectively. The findings from the experiments are shown in Table 3. The regression rate, oxidizer mass flux, and mass index uncertainties are 2.84 %, 9.22 %, and 9.47 % respectively.

As shown in Table 3, the 50 % H_2O_2 has a low regression rate. This is due to the 50 % water content which restricts the heat transfer from the flame to the grain surface and this ultimately results in a low regression rate as compared to the regression rate with pure gaseous oxygen. As the concentration of H_2O_2 increases the regression rate also increases due to reduced water quantity and thus heat transfer rate increases. Static firing with 90 % H_2O_2 gives more regression rate as compared to 50 % and 70 % H_2O_2.

The regression rate and oxidizer mass flux (Gox) power fit curves of 50 %, 70 %, and 90 % H_2O_2 are shown in Fig. 8. The regression rates obtained with 70 % and 90 % H_2O_2 are quite similar. However, as the concentration of H_2O_2 increases, the O/F ratio reduces, leading to a fuel-rich condition. The difference in the regression rate between 70 % and 90 % H_2O_2 seems insignificant. The regression rate of 1.93 mm/s was achieved with a 90 % concentration of H_2O_2. This rate is significantly higher than the one reported by Marothiya, *et al.*[10] which was less than 1 mm/s. The reason for this difference is the oxygen supply provided by H_2O_2 in comparison to their experiment which involved wax and aluminum fuel with 90 % concentration of H_2O_2 alone.

3.2 Combustion Efficiency Studies

Combustion efficiency is a crucial measure of the

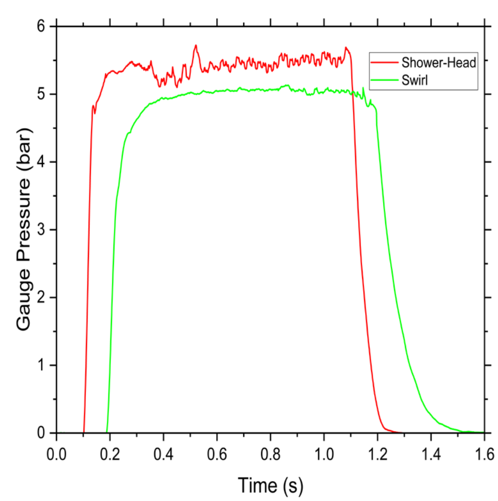


Figure 9. Pressure time curve with gaseous oxygen only for both injectors.

completeness of combustion of fuel and oxidizer in the combustion chamber. Hybrid rocket fuels have a major disadvantage of low combustion efficiency. Kim[4], *et al.* reported that a significant amount of droplets of entrained wax fuel left the motor without combustion affecting combustion efficiency. A higher specific impulse of a motor can be achieved by maximizing combustion efficiency. In this study, the effect of H_2O_2 concentration on the combustion efficiency of a paraffin wax-based fuel grain needs to be investigated.

3.2.1 *Firing with Swirl and Shower Head Injector with Gaseous Oxygen Only*

The pressure-time curve of the combustion chamber of a hybrid rocket motor after a static firing test was recorded using a pressure transducer for both swirl and showerhead injector and it is shown in Fig. 9.

A total of four sec. of firing with an interrupted test of 1 sec each was done in both cases. When using the showerhead injector, the gauge pressure inside the combustion chamber measured approximately 5.4 bar and 4.7 bar for the swirl injector case.

The combustion efficiency was calculated as discussed in section 2.4 and is shown in Table 4. Due to better combustion and pressure rise showerhead injector case, the combustion efficiency was seen to be higher than the swirl injector. Due to the increased regression rate in the case of swirl injection, the oxidizer concentration is reduced and hence less O/F and the mixing for a given length of the motor becomes less, indicating lower efficiency.

Table 4. Combustion efficiency of gaseous oxygen with PW with showerhead and swirl injector

Injector	O/F	Pc (Bar)	$\dot{m}_{tot}$ (g/s)	C^*_{theo} (m/s)	C^*_{exp} (m/s)	η_{C^*} (%)
Showerhead	0.72	5.40	67	1224.0	632.92	51.67
Swirl	0.47	4.70	76	1107.30	485.64	43.85

3.2.2 *Experiments with a 50 % Concentration of Hydrogen Peroxide and Gaseous Oxygen Combination*

The pressure-time curve of hydrogen peroxide with the PW fuel grain is shown in Fig. 10. It was observed from the experimentation that the ignition with H_2O_2 was not as simple as observed with the gaseous oxygen system. No catalyst was used for the decomposition of hydrogen peroxide. Hence, for stable ignition with H_2O_2, initially, gaseous oxygen was also used along with the solid propellant bead igniters.

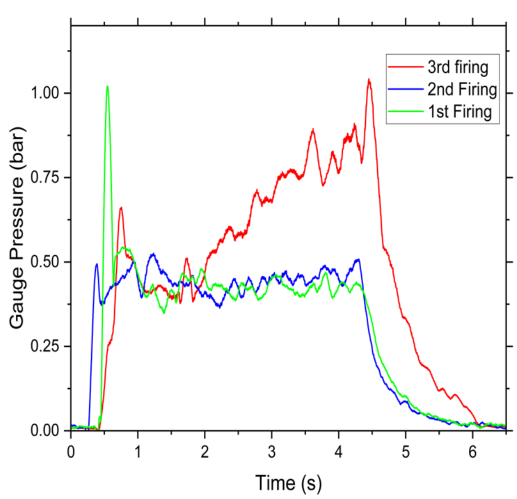
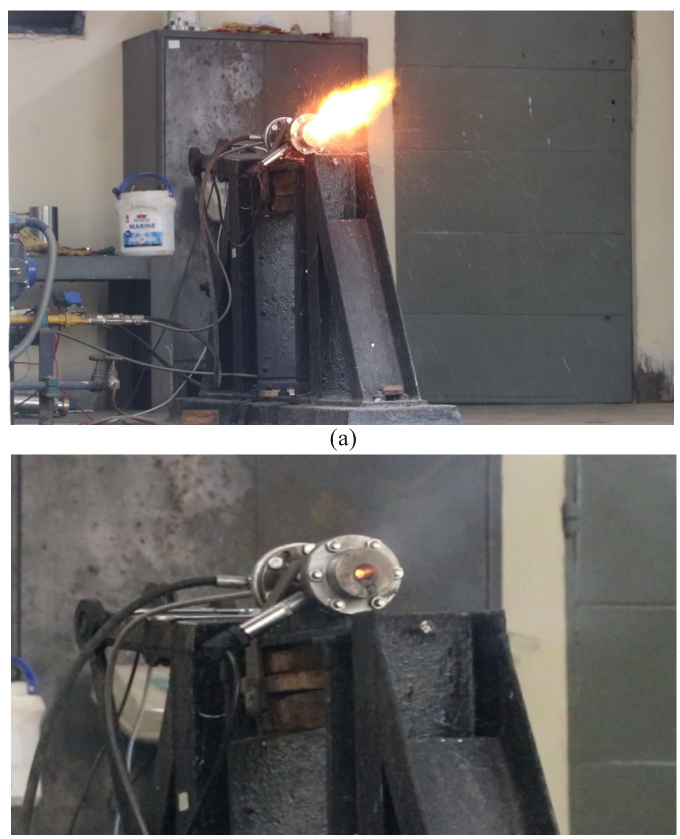


Figure 10. Pressure time curve with 50 % concentration of hydrogen peroxide and gaseous oxygen

In the first firing case, the oxygen was supplied for around 0.8 sec. for stable ignition before H_2O_2 would be injected. Figure 10 shows that the pressure increased significantly with the injection of gaseous oxygen, but then suddenly dropped after the injection of H_2O_2. It was observed that pure 50 % H_2O_2 was unable to sustain combustion without an oxygen supply, as evidenced by Fig. 11. Similar findings were also reported by Marothiya[10], *et al.*, where hydrogen peroxide alone was not able to sustain combustion when the oxygen supply was cut off. Hence, oxygen was also supplied with H_2O_2 throughout the firing for steady combustion in the next two firings. The combustion chamber experiences an average pressure rise of 0.5 bar. The pressure is low due to 50 % water content in H_2O_2 which helps in reducing the heat release from the endothermic reaction of H_2O_2 decomposition and the motor was not able to achieve nozzle chock condition. Figure 10 shows that initially, during the ignition phase, the pressure rise was higher. This happened because during the initial phase of around 0.8 sec, only oxygen was supplied as the oxidizer, and then 50 % H_2O_2 was injected. This reduced the combustion process in the chamber pressure. It is also important to note that the pressure peak in each firing keeps improving. Although manual drainage of H_2O_2 between each test was implemented, small amounts of peroxide residue remained adhered to internal surfaces and



(a)

(b)

Figure 11. Exhaust image of hybrid rocket motor (a) with oxygen and H_2O_2, and (b) with 50 % H_2O_2 alone.

this unburnt H_2O_2 remains within the combustion chamber in the liquid form continues reacting with the wax until the next firing is conducted, as observed from the 3rd firing data of Fig. 10. This reaction helps in increasing the regression rate as well as the pressure peak in each firing.

The combustion chamber experienced a low pressure rise which prevented the motor from reaching the nozzle chock condition, as the throat diameter of the nozzle was designed considering the complete combustion process between the fuel and oxidizer. As a result, it is not possible to calculate C* and combustion efficiency for the 50 % H_2O_2 case. The primary reason for this is the higher concentration of water in H_2O_2, which hinders complete combustion within the combustion chamber and also contributes to reducing the combustion caused by oxygen. It is also observed that most of the entrained fuel droplet leaves the motor without complete combustion.

3.2.3 Experimentations with a 70 % Concentration Hydrogen Peroxide and Gaseous Oxygen Combination

The pressure-time curve of 70 % hydrogen peroxide with the PW fuel grain is shown in Fig. 12. As discussed earlier, the graph displays three sets of firing data, each lasting for 3 sec.. The burn duration in this case was reduced to 3 sec. compared to the previous 50 % H_2O_2 case because the web thickness of the grain remained the same and a higher regression rate was expected. To avoid complete web thickness burning, the burn time duration was decreased.

During the first firing, the endothermic reaction of H_2O_2 was slow, resulting in less heat release during combustion and a much lower pressure rise as seen in Fig. 12. As PW was already heated up in the first firing due to the reaction of H_2O_2 continuing to take place with wax fuel, heat was released

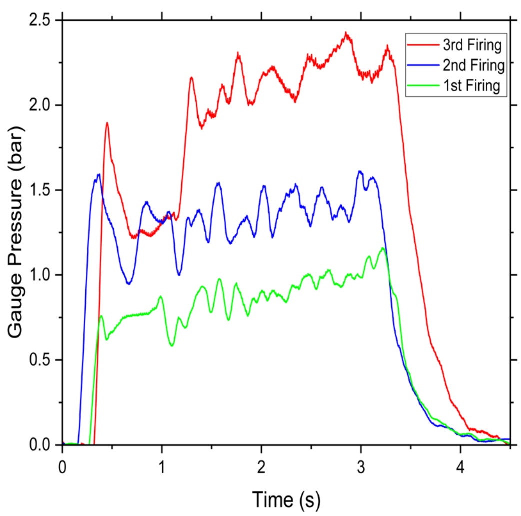


Figure 12. Pressure time curve with 70 % concentration of hydrogen peroxide and gaseous oxygen.

Table 5. Combustion efficiency of 70 % H_2O_2 and gaseous oxygen used in a 70:30 ratio

O/F	Pc (Bar)	$\dot{m}_{tot}$ (g/s)	C^*_{theo} (m/s)	C^*_{exp} (m/s)	η_{c^*} (%)
1.65	0.75	79	1439.70	-	-
1.35	1.25	90	1271.70	109.07	8.50
1.27	2.00	94	1264.10	167.09	13.46

more rapidly in the next firing resulting in more pressure rise in every subsequent firing. The maximum average chamber pressure was 2 bar, which is higher than that of 50 % H_2O_2. The combustion efficiency was very low for the 2nd and 3rd firing as shown in Table 5.

3.2.4 Experiments with a 90 % Concentration Hydrogen Peroxide and Gaseous Oxygen Combination

A 90 % concentration of hydrogen peroxide is a rocket-grade oxidizer that releases a large amount of heat during its endothermic decomposition reaction. Figure 13 depicts the pressure-time curve of 90 % hydrogen peroxide with the PW fuel grain. During firing, H_2O_2 and oxygen were supplied with a 70:30 ratio. The graph shows three sets of firing data, each with a duration of 2 sec.. To reduce burn duration, similar measures were taken as previously discussed. The peak pressure achieved in the combustion chamber was approximately 17.5 bar, while the average gauge pressure throughout the firing was around 7 bar. This is considerably higher than the pressures achieved in previous firings with 50 % and 70 % concentrations of hydrogen peroxide.

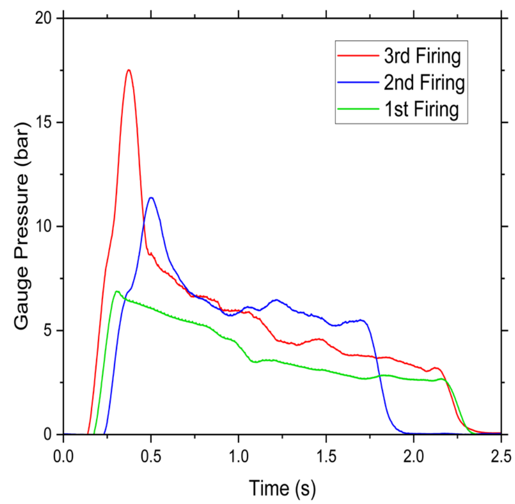


Figure 13. Pressure time curve with 90 % concentration of hydrogen peroxide and gaseous oxygen.

During firing, PW fuel reacts with hydrogen peroxide (H_2O_2). However, the endothermic reaction does not stop after firing, releasing more heat during the last firing. In each time interval of firing, the mass of H_2O_2 accumulated in the chamber keeps reacting and provides an enhanced chamber pressure. With the increased intervals of the test firing, the errors in the chamber pressure keeps increasing and it can be seen from the 3rd firing of Fig. 11. Due to this reason, the chamber pressure is seen to be significantly higher and efficiency is also observed to be significantly high as given in Table 6. This increased efficiency is also due to increased O/F after each sequence of the test firing. With a 90 % concentration of H_2O_2, the average thrust produced was 120 N. Table 6 shows that an average gauge pressure of 7 bar was obtained in the combustion chamber. This high pressure resulted in an increased combustion efficiency of around 60.20 %, compared to firings with lower concentrations of hydrogen peroxide.

Although, nitrogen purgeing along with manual drainage of H_2O_2 has been implemented after each test firing, small

Table 6. Combustion efficiency of 90 % H_2O_2 and gaseous oxygen used in a 70:30 ratio

O/F	Pc (Bar)	$\dot{m}_{tot}$ (g/s)	C^*_{theo} (m/s)	C^*_{exp} (m/s)	η_{c^*} (%)
1.50	5.00	70	1286.30	560.92	43.6
1.54	6.00	69	1300.90	682.86	52.49
1.36	10.00	74	1256.00	1061.21	84.5

amounts of peroxide residue remained adhered to internal surfaces of the hybrid rocket motor. It is important to note that these residues was small compared to the injected flow still it contributes to the addititional heat release and local temperature rise influenced the fuel regression rate and combustion efficiency. This effect is clearly visible in the increasing trends of those parameters across each sequential firings. However, this phenomenon is not merely an experimental artifact it reflects a realistic operating scenario in practical hybrid rocket engines. One of the key advantages of hybrid systems is their throttleability and restart capability. In operational missions, if a hybrid engine is restarted shortly after shutdown; similar thermal and chemical memory effects due to residual oxidizer would influence the ignition and combustion dynamics. Thus, our test design intentionally captured these effects by evaluating the engine's performance during multiple successive firings, to explore such restart behaviour.

3.3 Summary

A comparison of test results using 50 %, 70 %, and 90 % hydrogen peroxide is given in Table 7 and it shows a clear improvement in performance as the concentration increases. The 50 % H_2O_2 had poor ignition and unstable combustion, with the flame going out repeatedly. This was mainly due to the high water content, which cooled the flame and made it hard to burn. With 70 % H_2O_2, ignition lasted longer, and the flame was more stable. It showed better results, with a fuel regression rate of about 1.57 mm/s and combustion efficiency of 13.46 %. However, performance was still limited by the remaining water. The best results came from the 90 % H_2O_2, which burned steadily with a strong flame and needed much less gaseous oxygen to keep burning. It reached the highest fuel regression rate of 1.93 mm/s and a combustion efficiency of 67.6 %. Less unburned residue was seen after the test, and the flame was more uniform. These findings clearly show that higher concentrations of H_2O_2 help improve combustion by releasing more heat and burning the fuel more completely, so higher concentrations of 90 % more are most effective for hybrid rocket engines.

4. CONCLUSIONS

Experimental investigation has been carried out on the use of hydrogen peroxide as an oxidizer. The study employed three different concentrations of hydrogen peroxide, namely 50 %, 70 %, and 90 %. The 70 % and 90 % concentrations of hydrogen peroxide were obtained from a 50 % concentration of H_2O_2 using a rotary distillation unit in the laboratory. To ignite the hydrogen peroxide inside the combustion chamber, a solid composite propellant bead igniter was used without any catalyst for H_2O_2 decomposition. Since hydrogen peroxide requires a catalyst to decompose, oxygen was used as an alternative to ignite, initiate and sustain the combustion. Based on the results of these experiments, the following conclusions can be drawn:

Achieving steady combustion at lower concentrations of H_2O_2 is difficult and would require a catalyst to decompose it faster and release more heat to improve combustion efficiency.

It is not advisable to use lower concentrations of hydrogen peroxide (H_2O_2) as lower concentrations are less effective due to higher water content, which acts as a flame quencher.

While paraffin wax has a high regression rate in hybrid rockets, its regression rate is very low with lower concentrations of hydrogen peroxide. Increasing the concentration of H_2O_2 increases the reaction rate with PW, resulting in faster fuel burn.

Combustion efficiency varies with the concentration of H_2O_2. The average combustion efficiency for a 90 % concentration of a 70:30 H_2O_2 and O_2 mixture was around 60.2 %, whereas, for a 70 % concentration of H_2O_2, the combustion efficiency was only 10.98 %.

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Table 7. Summary of combustion characteristics with different H_2O_2 concentrations

Parameters	H_2O_2 (50 %) + GOX	H_2O_2 (70 %) + GOX	H_2O_2 (90 %) + GOX
Ignitability	Poor	Moderate	Good
Combustion stability	Unstable / Interrupted	Intermittent	Stable
Highest regression rate (mm/s)	0.5	1.57	1.93
Combustion efficiency (%), 3rd firing	-	13.46	84.5
Flame behavior	Weak / Self-extinguishing	Weak	Strong and sustained
Visible residue post-test	High	Moderate	Low
Required GOX flow for ignition	High	Moderate	Low

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His contribution in the current study includes: Conceptualization, writing, reviewing, and editing.