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

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1 Introduction

Hybrid rocket propulsion systems combine the benefits of solid and liquid technologies, using a combustion chamber with solid fuel and a separate liquid or gaseous oxidizer tank [1]. The solid fuel, typically paraffin or high-density polyethylene, is stable and easy to handle, while the oxidizer, stored in liquid form, enables controlled combustion. A pyrotechnic igniter is usually needed to start combustion, especially for non-hypergolic fuel combinations [2-3].

Hybrid rockets are safer than solid rockets due to a reduced explosion risk and offer better thrust controllability, allowing precise flight maneuvering by regulating the oxidizer flow rate. Optimizing hybrid rocket combustion is complex, as factors like fuel grain geometry, oxidizer flow, and chamber pressure affect performance [4]. Low thrust from a low regression rate has prompted research into designs like protrusions [5], bluff bodies [6], and swirl injectors [7] to improve fuel burn. Recent studies focus on simpler oxidizer-based motor designs.

Hybrid rocket systems, 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 rockets 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 et al. [9] showed a high performance of 75 KN thrust by using paraffin wax and liquid oxygen combination. Similarly, Gaurav et al. [10] 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 et al. [11] discovered that adding metal additives like aluminum and boron increased the energy density of paraffin-based fuels for hybrid rockets. David et al. [12] demonstrated enhanced ignition of solid hydrocarbon fuel through the utilization of a 90% concentration of hydrogen peroxide. Whitmore et al. [13-14] delved into the performance of ABS fuel when combined with H_2O_2 and gaseous oxygen (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 et al. [15-16] and hydroxyl-terminated polybutadiene by Rajesh et al. [17]. Additionally, a study by Thoine et al. [18] 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 et al. [19] 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 et al. [20] 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.

With rising environmental concerns, the rocket industry is shifting to green propulsion. Hydrogen peroxide (H_2O_2) is a promising oxidizer, but its ignitability and performance variations without a catalyst need further study. Paraffin wax (PW), with a four times higher regression rate than HTPB, is an eco-friendly, cost-effective fuel. This paper analyzes combustion complexity by varying H_2O_2 concentration with GOX using PW.

2 Experimental procedure and setup

2.1 Preparation of rocket-grade hydrogen peroxide and paraffin wax fuel grain (PW)

Hydrogen peroxide (H_2O_2) is a strong oxidizer that decomposes exothermically into water and oxygen [21]. High-Test Peroxide (HTP, >70% H_2O_2) is widely used in rockets and industry. To achieve high concentration, a 50% solution is safely evaporated using a rotary evaporator under vacuum conditions [22]. H_2O_2 solutions of 70% and 90% were obtained and verified using a refractometer, measuring refractive index and specific gravity with uncertainties of 0.08% and 1.07%, respectively. The concentration-refractive index correlation aligns with existing literature [23].

A solid Paraffin wax (PW) fuel grain with an annular center port was made using a mandrel and a mould, following the procedure adopted by Dinesh et al. [24]. The fuel density was determined as 910 kg/m³ via the water displacement method, with an uncertainty of around 6%.

2.2 Experimental setup

The fluid systems were designed with minimal complexity and redundant safety components, to ensure accurate combustion monitoring. Figure 1 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. The entire fluid system is made of SS316, which can withstand high concentrations of hydrogen peroxide.

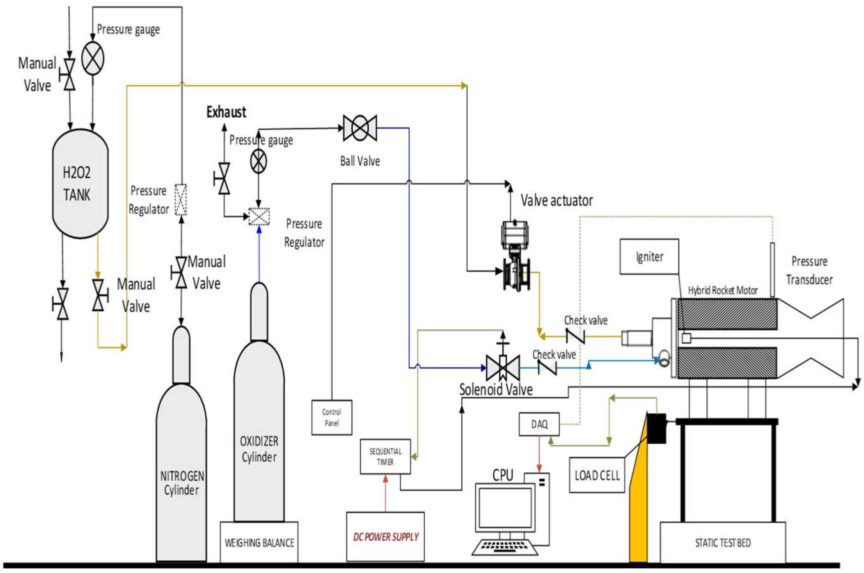


Figure 1: Schematic view of hybrid rockets experimental setup

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 150 psi was applied. A sequential timer (Selec, PT-380) with a least count of 0.01 seconds was connected to the solenoid valve, which would automatically disconnect after a predetermined set time. The UNIK 5000 pressure transducer was used with a pressure range of 0 to 50 bars. A pressure transducer was mounted 30 mm upstream of the nozzle. 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. 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 nozzle with a 10mm throat diameter is made up of stainless steel with an inner layer having graphite to withstand the high temperature of the combustion product.

3 Result and Discussion

3.1 Regression rate studies

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. To decompose H_2O_2, high heat is required. 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 H_2O_2 supply while the swirl part was connected to the oxygen supply. The swirl component of oxygen helps to improve the atomization of H_2O_2 by supplying gaseous oxygen tangentially. 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 300 psi and a 20 g/s mass flow rate. The mass flow rate of gaseous oxygen was 8 g/s at 400 psi. The H_2O_2 and oxygen gas were injected into the combustion chamber in a 70:30 ratio for each concentration of H_2O_2.

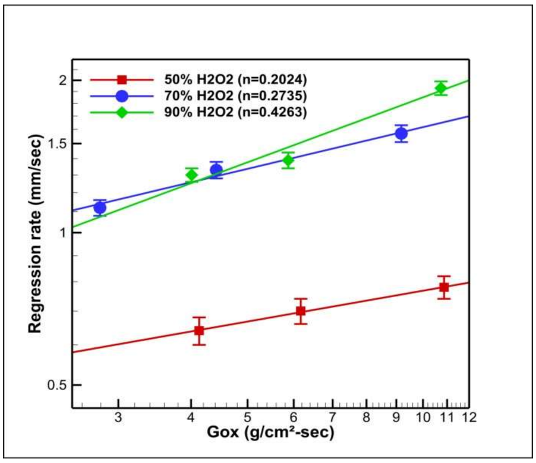
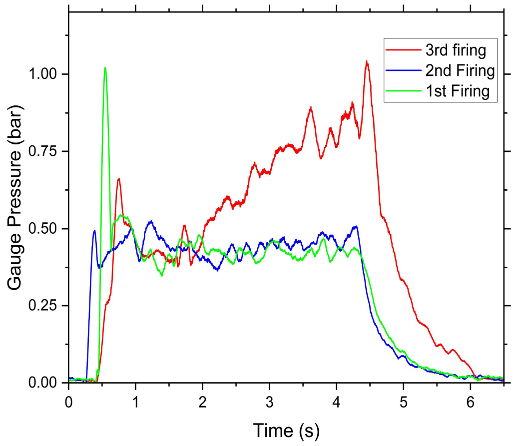


Figure 2: Regression rate v/s oxidizer mass flow power fit curve for 50%, 70%, and 90% H_2O_2

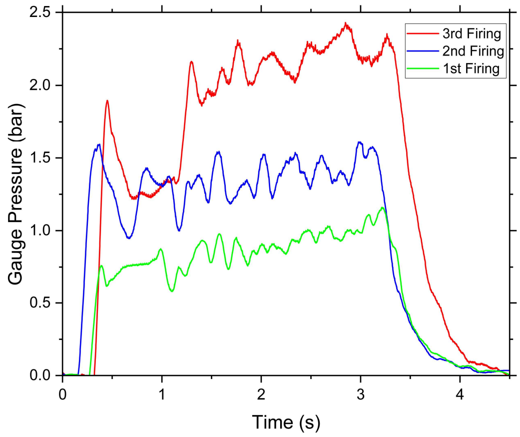
Three static firings were conducted for each 50%, 70%, and 90% concentrated hydrogen peroxide with a burn time of 4, 3, and 2 secs, respectively. The regression rate and oxidizer mass flux (Gox) power fit curves of 50%, 70%, and 90% H_2O_2 are shown in Figure 2. As shown here, the 50% H_2O_2 has a low 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. 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

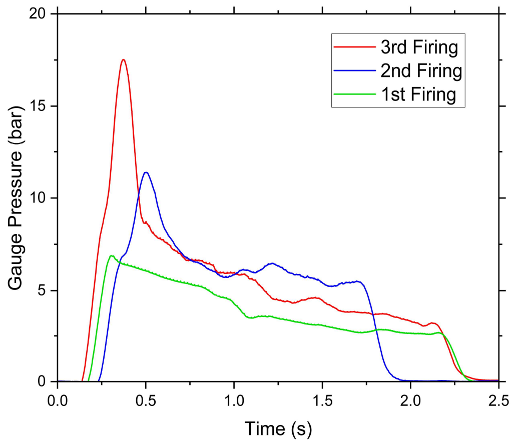
Hybrid rocket fuels have a major disadvantage of low combustion efficiency. Kim et al. [4] reported that a significant amount of droplets of entrained wax fuel left the motor without combustion affecting combustion efficiency. A higher specific impulse of a motor can be achieved by maximizing combustion efficiency. 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.



(a)



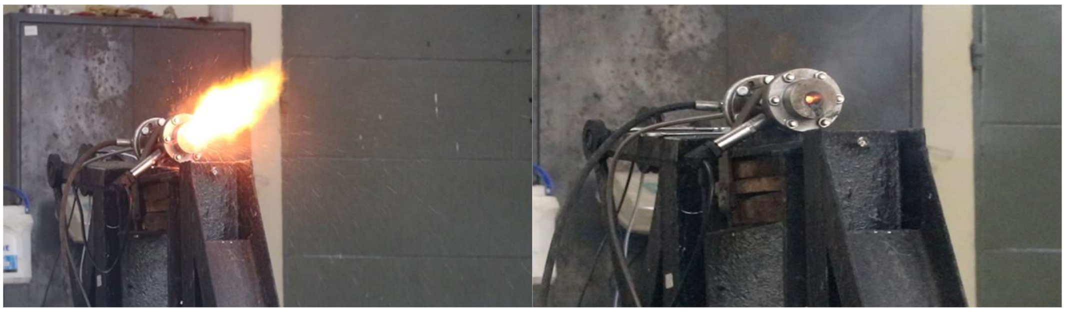
(b)



(c)

Figure 3: Pressure time curve (a) with 50% concentration of H_2O_2 (b) with 70% concentration of H_2O_2 (c) with 90% concentration of H_2O_2

In the first firing case i.e. 50% H_2O_2, the oxygen was supplied for around 0.8 sec for stable ignition before H_2O_2 would be injected. Figure 3 (a) 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 oxygen supply, as evidenced by Figure 4 (b). Similar findings were also reported by Marothiya et al. [10], 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. As a result, it is not possible to calculate C* and combustion efficiency for the 50% H_2O_2 case. Figure 3 (a) shows a higher pressure rise during the ignition phase, as only oxygen was supplied initially, followed by 50% H_2O_2 injection at around 0.8 sec. This reduced chamber pressure. Notably, the pressure peak improves with each firing, as unburnt H_2O_2 remains in the chamber in liquid form and continues reacting with the wax, increasing the regression rate and pressure peak, as seen in the 3rd firing data.



(a) (b)

Figure 4: Exhaust image of hybrid rocket motor (a) with oxygen and 50% H_2O_2 (b) with 50% H_2O_2 alone

The pressure-time curve of 70% H_2O_2 with the PW fuel grain is shown in Figure 3. (b). The burn duration in this case was reduced to 3 seconds 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 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 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 70% H_2O_2.

A 90% concentration of H_2O_2 is a rocket-grade oxidizer that releases a large amount of heat during its endothermic decomposition reaction. Figure 3 (c) shows three sets of firing data with 90% H_2O_2, each with a duration of 2 seconds. 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 70% H_2O_2. During firing, PW fuel reacts with H_2O_2. However, the endothermic reaction does not stop after firing, releasing more heat during the last firing. This leads to a significant increase in pressure, which can be dangerous. With a 90% concentration of H_2O_2, the average thrust produced was 120 N. This high pressure resulted in an increased combustion efficiency of around 60.20%, compared to firings with lower concentrations of 70% H_2O_2.

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