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BURNING OF POLYETHYLENE WITH HYDROGEN PEROXIDE IN A 2D SLAB COMBUSTOR

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Abstract. Hybrid propulsion systems have higher security operation, less complex design and lower operational and developmental costs than liquid bipropellant systems. Hydrogen peroxide (H_2O_2) is a high-density green propellant which decomposes above $600\text{ }^\circ\text{C}$ for concentrations in aqueous solutions higher than 85% weight/weight. A combustion chamber with a quartz window was designed and built for the study of the burning process of high density polyethylene with high concentrated hydrogen peroxide. A catalytic bed, filled with a cobalt, manganese, and aluminum oxide based bulk catalyst, was used for decomposition of the H_2O_2 and injection of decomposition products into the combustion chamber. Rectangular grains of polyethylene fuel were prepared and burned for analysis of the spatial and temporal variation of the regression rate. Analyses of the influence of the oxidizer fluxes over the fuel grain were performed and power laws for the regression rates were determined. There was formation of lumps at the port inlet of the grains, creating adjacent recirculation zones that favored ignition and flame anchorage.

Keywords: Hybrid rocket propulsion, High density polyethylene, Hydrogen peroxide, Regression rate

1. INTRODUCTION

Hybrid rocket propulsion technology has been known for almost a century, but since the 1980s it has been concerned with the safety of propulsive systems, mainly as a result of the explosions of solid-propulsion boosters from Space Shuttle and other rocket launchers, induced to the resumption of its development. The relatively safe operation of hybrid propulsion systems is associated with the physical separation of fuel and oxidizer, unlike solid propellant propulsion systems in which the fuel and oxidizer are pre-mixed.

In the last decades, there has been a growing interest in the development of new propulsive systems that combine low cost, low environmental impact and shorter development time, particularly for launch of nano-satellites, sounding rockets, scientific experiments and sub-orbital tourism.

Moore et al. (1954) related the use of high density polyethylene (HDPE) as fuel in rocket propulsion systems. HDPE is easy to machine, relatively cheap, has high mechanical resistance and presents higher regression rate in comparison with polymethyl methacrylate (PMMA) and hydroxyl-terminated polybutadiene (HTPB).

Hydrogen peroxide (H_2O_2) aqueous solution is a relatively low-cost, low-toxicity oxidizer which decomposed, produces only water (H_2O) and oxygen (O_2) at elevated temperatures depending on the concentration.

Studies related to the use of polyethylene and aqueous solutions of hydrogen peroxide as propellants in hybrid propulsion systems have been made since the 1950's (Moore and Berman, 1956; Bettner and Humble, 1998; and Tsujikado and Ishihara, 2008). However, the ballistic properties of the oxidizer flow throughout the combustion chamber were rarely investigated in detail, since, in general, conventional rocket motors are used, and closed combustion chambers usually do not permit the instantaneous analysis of the fuel consumption profile, and only measurements of thrust, temperature, pressure and average data of mass or geometry changes can be made.

In this work, a visual analysis of the fuel grain burning is presented. By means of direct visualization of the fuel grain during its burning process, data is generated to characterize the regression rate of HDPE, besides analyzing the influences of the oxidizer flux and geometry of the fuel grain has on ignition delay and consumption profile of the fuel surface.

2. EXPERIMENTAL SETUP

In the last decade, some research groups around the world have proposed the use of two-dimensional combustion chambers with transparent window, burning different fuels with pure oxygen (O_2) as shown in the Fig. 1.

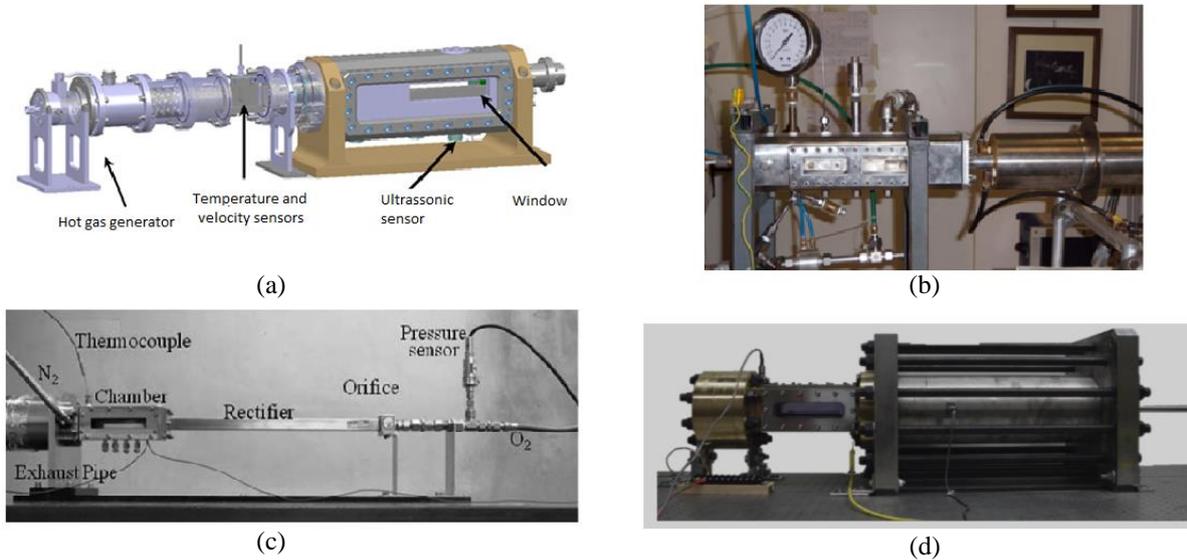


Figure 1. Hybrid propellant combustor, with transparent window, to burn: (a) Paraffin fuel and hot products of burning hydrogen and oxygen (Pelletier, 2009), (b), (c), (d) Paraffin based fuel and O_2 (Merotto et al., 2011; Nakagawa and Hikone, 2011 and Chandler et al., 2012).

Through this type of experimental apparatus, it is possible to observe in details the spatial and temporal evolution of the fuel surface consumption.

Differently from these cited studies, this work proposes using hydrogen peroxide solutions in concentrations of 85 and 90% weight by weight (w/w), decomposed at room temperature by a bulk catalyst made of Cobalt (Co), Manganese (Mn) and Aluminum (Al) as in Maia et al., 2014.

Figure 2 shows a 3D CAD picture of the combustor and catalyst bed used in this study.

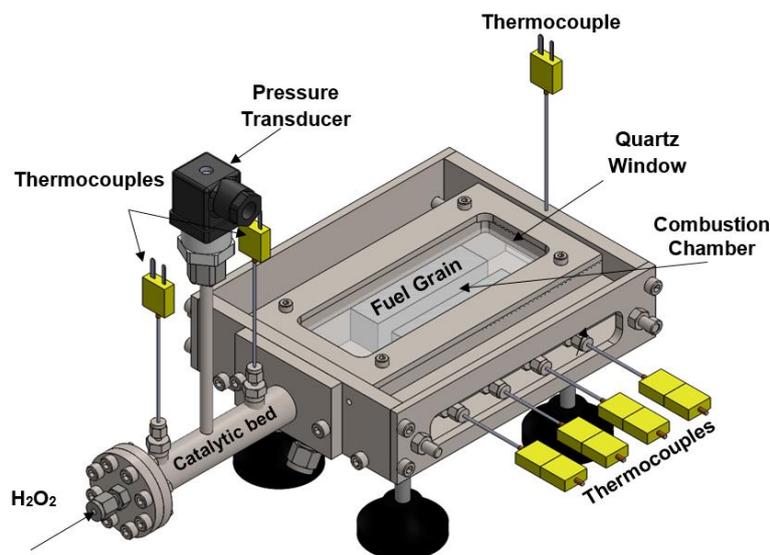


Figure 2. 3D CAD picture of the 2D slab combustor.

3. METHODOLOGY

Liquid hydrogen peroxide with concentrations of 85 and 90% w/w at room temperature is injected into the catalytic bed, where it is decomposed generating water vapor (H₂O) and gaseous oxygen (O₂) at temperatures above 600 ° C. The decomposition products enter into the combustion chamber, with temperature high enough to spontaneously ignite the fuel.

Each test was filmed with a high speed and high resolution camera, whose images were then analyzed with the open source software, *Image J*, as shown in Fig. 3.

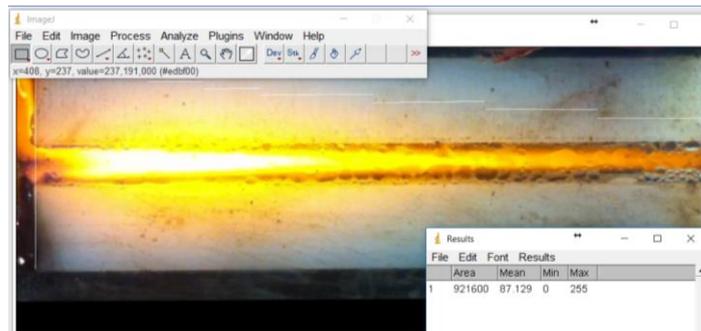


Figure 3. Video frame of burning polyethylene in *Image J*.

Through the video frame analysis, the instantaneous average height of the combustion port (\bar{H}), together with oxidizer mass flow rate (\dot{m}_{ox}) data, acquired by the datalogger, the averaged oxidizer mass flux (\bar{G}_{ox}) and spatial regression rate (\bar{r}) can be calculated, according to the procedure described below.

The first step is to determine the instantaneous averaged spatial height of the combustion port at the beginning and end of the burning time interval (t_b), as explicit in Fig. 4 and Eq. 1.

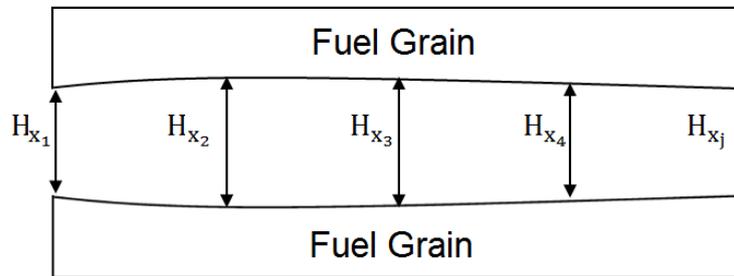


Figure 4. Averaged spatial height of the combustion port.

$$\bar{H}_t = \frac{\sum_1^j H_{x_j}}{j} \quad (1)$$

Where, x , is the axial position on the fuel grain surface relatively to the head end, and j is the number of divisions chosen to better describe possible axial variations in the behavior of the surface consumption.

With these port average values, the averaged spatial regression rate is then calculated by:

$$\bar{r} = \frac{\bar{H}_f - \bar{H}_i}{2(t_f - t_i)} \quad (2)$$

with the subscripts f and i referring to the initial and final instants of the analysis interval.

The averaged oxidizer mass flux can be calculated as:

$$\bar{G}_{ox} = \frac{\dot{m}_{ox}}{W \left(\frac{\bar{H}_i + \bar{H}_f}{2} \right)} \quad (3)$$

where W is the fuel grain width.

Finally, the coefficients a and n of the classical regression rate power law (Eq. 4) is obtained from the linear regression of the logarithmic values of \bar{r} and \bar{G}_{ox} .

$$\bar{r} = a \bar{G}_{ox}^n \quad (4)$$

4. RESULTS AND DISCUSSION

Figure 5 shows photographs of a pair of rectangular shaped HDPE grain burning with 85% H_2O_2 , depicting possible to observe the temporal and spatial evolution of the fuel burning surface profile.

In most tests carried out with HDPE, there was formation of a softened fuel elevation at the port inlet, causing the recirculation of gases and increasing of the convective heat transfer to the fuel, favoring ignition and flame anchorage, besides augmenting the local regression rate.

After ignition, the HDPE grains melt and form a high viscosity liquid layer over the entire surface of the solid fuel, which is carried out relatively slowly by the oxidizer flow, and a flame develops through the entire fuel surface.

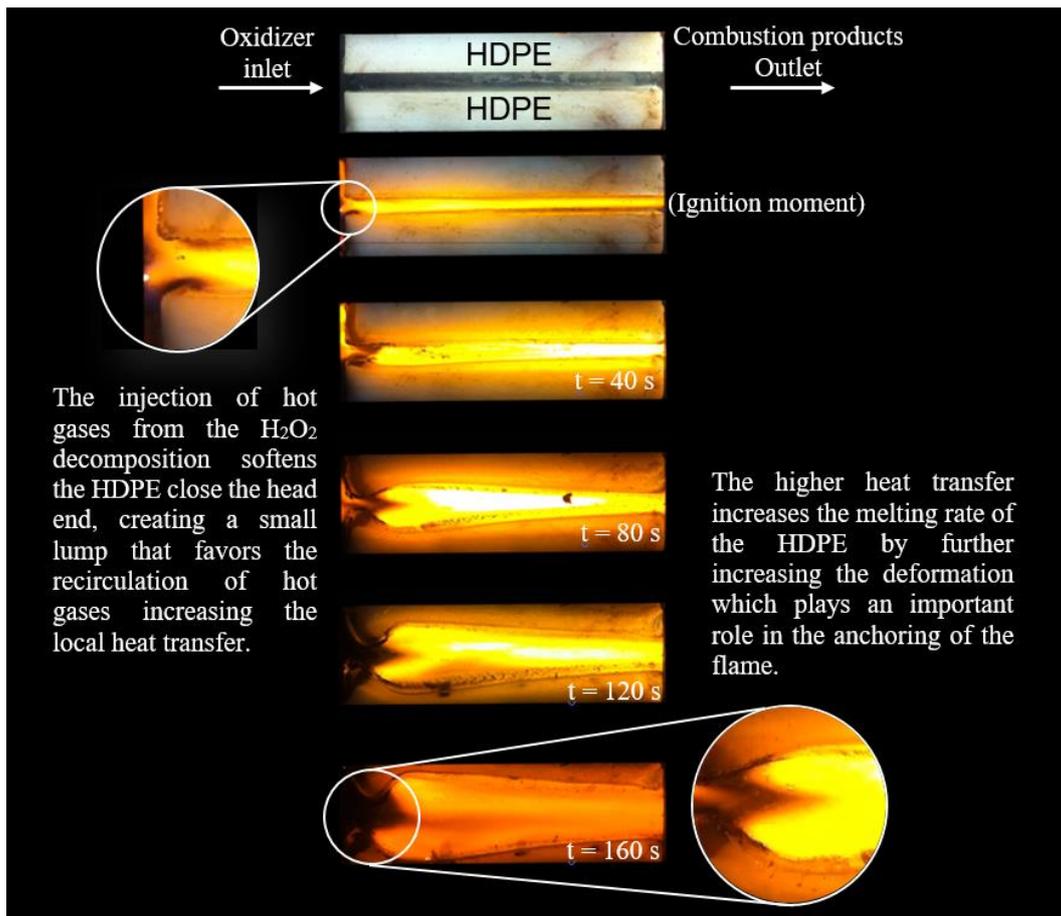


Figure 5. Photographs of a typical firing test of burning HDPE with H_2O_2 (85%).

Table 1 shows the operational conditions for the test presented in Figure 5.

Table 1. Operational conditions for test in Figure 5.

H ₂ O ₂ concentration (%)	85
Fuel grain width (mm)	20
Fuel grain length (mm)	122
Fuel grain height (mm)	20
Number of grains	2
Oxidizer mass flow (g/s)	1,5
Total time of test (s)	200

In order to further investigate about the influence of the lump formed at the port entrance on the ignition delay and flame anchorage, some tests with a chamfered HDPE grain (Fig. 6) were performed. In this geometry, the straight corner of the fuel at the head end was removed, making harder the formation of the recirculation region discussed before.

In this new condition, the fuel continued to melt due to injection of hot gases, but spontaneous fuel ignition never happened. Since ignition of the fuel was forcibly attained, a pilot flame of 1700 °C was used, as shown in Fig.7.



Figure 6: Chamfered HDPE grain.

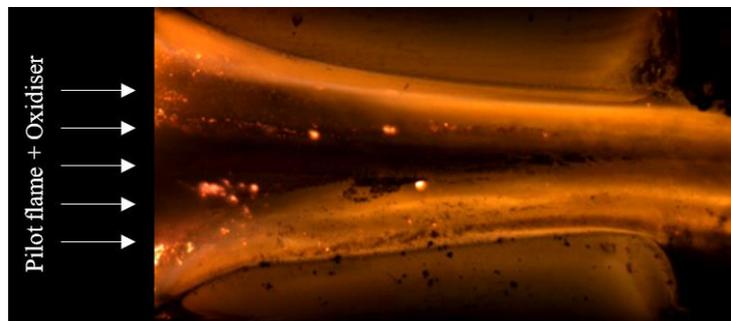


Figure 7: Chamfered HDPE grain burning in presence of pilot flame.

There was ignition, but in the absence of this strong external heat supply, the flame extinguished rapidly, clearly showing the importance of the recirculation zone for the combustion of these propellants. Another point is that the regression profile was totally different from the original grain, making clear the need for further studies, in order to characterize the effects that the flow behavior has on the regression rate profile, at least when using peroxide of hydrogen as an oxidant.

To prove the hypothesis that the formation of a lump and subsequently a groove, was essential for the good burning of HDPE / H₂O₂, it was proposed the use of grain with a previously made groove, simulating what naturally happened in the initial operation of the combustion chamber and the result can be seen in Fig. 8.

It was noticed, that the burning behavior was very similar that found in grains without any modifications, but the ignition delay decreased considerably, making this type of simple artifice of great significance, requiring further research investigation in order to optimize the results. The regression rate also maintained a profile and values similar to those originally found.

With respect to use H₂O₂ as oxidizer, an important observation was that, although its decomposition generates O₂ at 600°C or higher, enough to auto ignite the fuel, about 350°C, the large amount of water present in the combustion port, the high flow velocity and the decrease in temperature due the gases expansion when injected in combustion chamber, made it difficult to ignite the HDPE and anchor the flame over the grain, taking dozens of seconds to auto ignite the fuel, that is not a desirable characteristic.

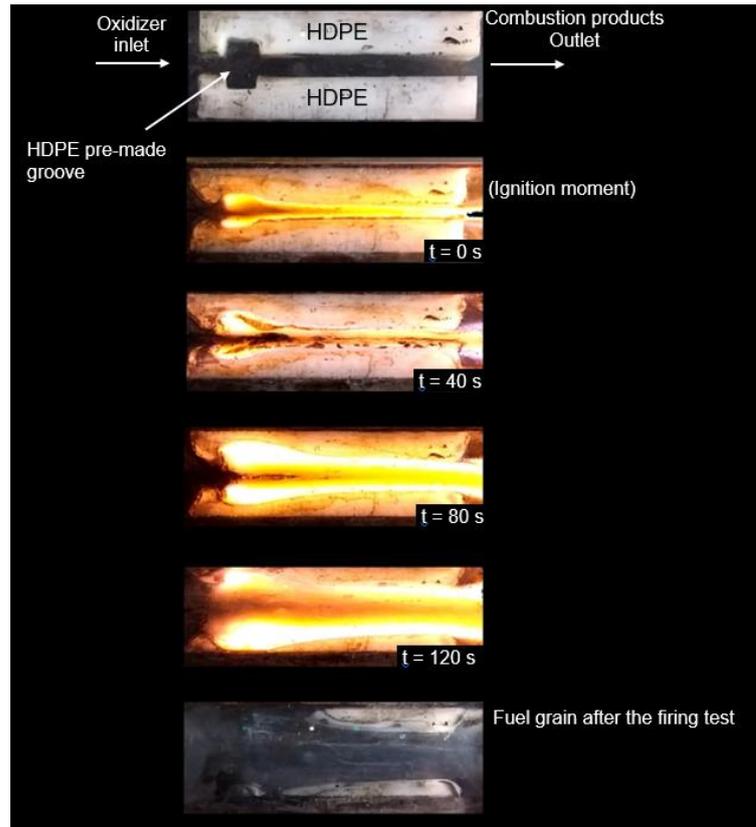


Figure 8: Chamfered HDPE grain burning with a previously made groove.

Figure 9 shows the deposition of water over fuel surface, due the vapor resulted of the catalytic decomposition of H_2O_2 .

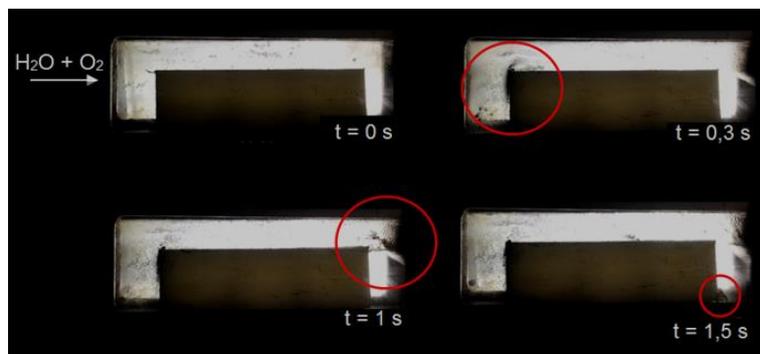


Figure 9: Water deposition over the fuel grains surface.

Through the images and data obtained during burning tests of parallelepiped grains, as described before, power laws for the regression rates of HDPE with an 85 and 90% w/w were obtained, as depicted in Tab. 2.

Table 2. Power laws of regression rates of HDPE/ H_2O_2 85 and 90% w/w.

H_2O_2 (%)	Oxidizer mass flux (\bar{G}_{ox}) (kg/m ² s)	Average regression rate (mm/s)
85	3 - 8	$\dot{r} = 18 \times 10^{-3} \bar{G}_{ox}^{0,70}$
90	7 - 14	$\dot{r} = 18 \times 10^{-3} \bar{G}_{ox}^{0,75}$

5. CONCLUSIONS

The catalytic decomposition of H_2O_2 85% w/w, or higher, reaches a sufficiently high temperature for autoignition of HDPE, but due to the large fraction of water present in the product gases, with water condensation on the grain and high speed of the flow make it difficult to ignite the fuel.

Despite HDPE fuels exhibit high mechanical and thermal resistance, when exposed to the hot decomposition products of H_2O_2 they are softened and generate recirculation zones that favor ignition and support the burning process without major instabilities. The formation of a lump at the grain port inlet has been observed in all rectangular grains tested. Tests with different fuel grain profiles have shown the large influence of the formation of recirculation zones on the ignition and anchoring the flame over the grain.

The disadvantage of using polyethylene in high thrust propulsion systems lies in its relatively low regression rate, and in the non-uniform burning along the grain length. Therefore, it is necessary to establish combustion chamber and grain geometries that favor its uniform burning.

High concentrated hydrogen peroxide from commercial peroxide 70% w/w is safe and stable, and can be catalytically decomposed generating gases in temperatures high enough to ignite most fuels. Nevertheless, its inherent high concentration of water, from the aqueous solution and from catalytic decomposition, must be considered, since water vapor may condense on the grain surface, reduces convection heat transfer to the grain, decreases combustion temperatures and make difficult the ignition.

6. ACKNOWLEDGEMENTS

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