Measurement of Solid Fuel Regression Utilizing Pixel Analysis in an Optical Hybrid Rocket Engine

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Abstract

The focus of this research work was to develop a data reduction method where fuel regression rates and flame contours, and other combustion chamber characteristics could be measured and observed inside of an optically accessible hybrid rocket engine. The engine utilized reactants of hydroxyl terminated polybutadiene (HTPB) fuels and gaseous oxygen. A method of pixel analysis was generated with ImageJ to make fuel regression measurements at small time and axial increments. Various regression measurements were made at multiple axial locations and time steps. Luminous flame zones were also successfully imaged on the length of the full fuel grain and leading edge. For the current experimental series, two sets of Plexiglas windows were used to capture combustion at 2000 to 4000 frames per second with a Phantom V310 high-speed camera. The engine maintained high chamber pressures up to 5 MPa while producing thrust levels of 100 to 300 N.

Introduction

Motivations for Studying:

- Fuel regression is a heavily studied topic in the hybrid propulsion field. Regression rates of various fuels vary with time an axial distance due to the mechanics of the combustion.
- From these images, a magnitude of combustion characteristics can be measured

Project Objectives:

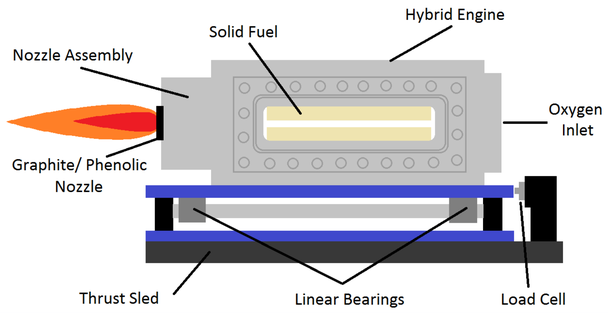
- Ascertain high-speed images of solid fuels instantaneously burning under real conditions and correlate regression rates using fundamental principles to obtain models.
- Create pixel analysis code in which regression rates of fuel can be measured at small time step along multiple fuel section indices.

Background:

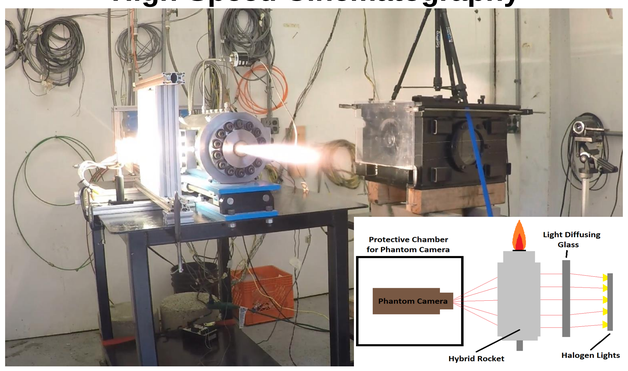
- Solid rockets are unable to be shut down once ignition occurs. In a hybrid rocket engine, fuel and oxidizers are stored separate from one other in two different phases. This allows the engine's thrust and fuel burning rate to be throttled to maximize vehicle performance. Even more important, hybrid engines can be shutdown during an emergency.

Significance on Field & Society

- Develop a more accurate models for solid fuel regression.
- Eliminate chlorine containing exhaust gases.
- Safer form of propulsion for human payloads.
- Provide a safer and cheaper form of propulsion in terms of production and handling/ storage.

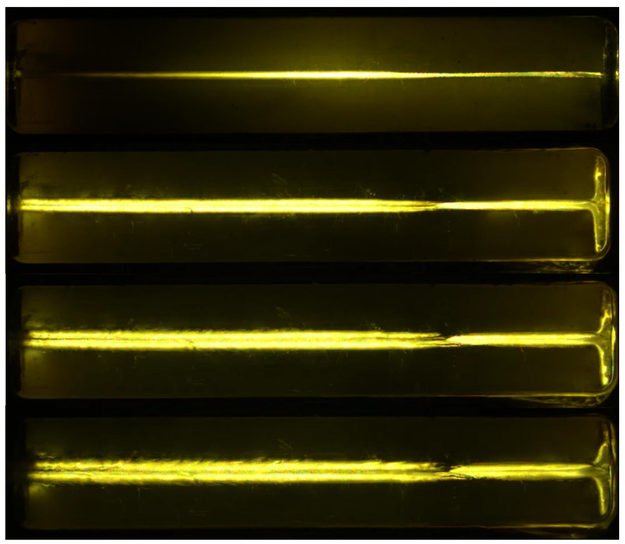


High-Speed Cinematography



- A system of powerful halogen lights, diffusing glass, filters, and a high-speed camera were used to capture the combustion event inside the engine.
- Halogen lighting illuminated the two fuel slabs in order to block out most of the luminosity for the combustion. This provided a nominal background for imaging.
- The camera was placed inside of a steel box to protect it from the very energetic event of firing the engine.

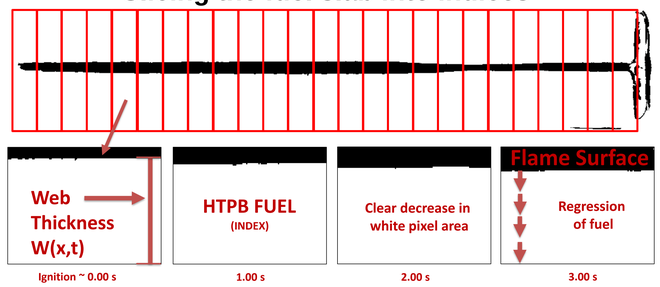
Images of Combustion and Fuel Regression



Reduction Code Methodology

- The reduction code converts the image into 8-bit. It then applies a color compression filter and uses a two-color threshold. This turns the image into only black and white pixels. Aiding the code in analysis.

Slicing the fuel slab into indices



- To make axial measurements, the fuel grain was divided into indices to set length Lx. The fuel web height, W(x,t), is the total height of the fuel in each respective index. Regression, or the burring rate of the fuel, can be calculated by taking the difference in area between two time step images in one index and diving it by the time difference multiplied by index length

$$W(x,t) = \frac{Area(x,t)}{L_x} \qquad r_b(x,t) = \frac{A_1(x,t) - A_2(x,t)}{L_x(t_2 - t_1)}$$

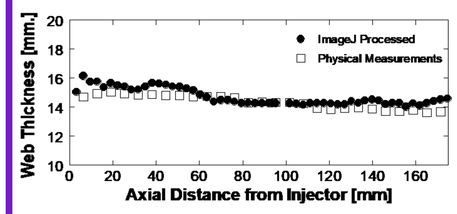
Governing Equations of Regression

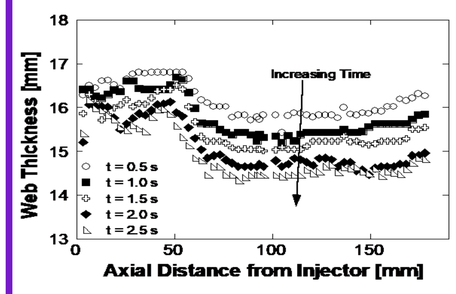
$$G_{ox}(x,t) = \frac{\dot{m}_{ox}}{A_{cs}(x,t)} \qquad G_{total}(x,t) = \frac{\dot{m}_{ox} + \dot{m}_{fuel}(x,t)}{A_{cs}(x,t)}$$

$$r_b = a_0 {G_{ox}}^n$$

The terms a_0 and n depend on fuel and oxidizer choice

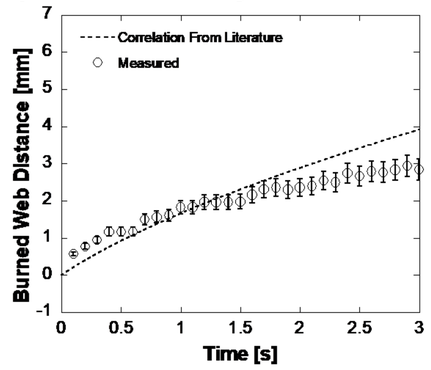
Graphs Generate by Reduction Code





- The graph to the left represent the web thickness verse axial distance from the oxygen injector.
- Featured to the left is web thickness at different time indices. The difference between the thickness divided by step time represents a rough burning rate aka regression.

Graphs Generate by Reduction Code



- The burned web distance was compared to a theoretical model derived from past literature. The measurements made by the reduction code followed that of literature well. The slope of this line correlates to the regression rate (burning rate) of the HTPB fuel.

Conclusions

- Modification of the engine's windows were successfully made. These modifications allowed images with higher magnitude of clarity, allowing pixel analysis to be employed.
- A system of high-powered halogen lights, diffusing glass, and filters were used with a Phantom V310 camera to obtain some of the only videos of fuel regression inside of a high-pressure environment in a hybrid engine.
- A reduction code, which makes tens of thousands of measurements, was created. This code utilized a software called ImageJ. The code utilized pixel analysis where the fuel grain regression could be determined at any axial location and any time step. Other parameters such as fluxes, flow rates, and correctional areas could be calculated with this code.

Future Work

- Install quartz sacrificial windows to ensure constant port wide and provide clear access to the combustion process.
- Embed fine-wire microthermocouples in the subsurface of the solid fuel slabs to obtain thermal wave thickness, surface temperate, and activation energy of the solid fuel.
- Investigate other fuels like PBAN, Delrin, Aluminized HTPB and Paraffin Wax.

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