Peering Inside an Ignited Hybrid Rocket

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Abstract: The regression rate is a fundamental parameter and is explained in depth. It is key to understanding the thrust performance, the low regression rates experienced in hybrid rockets, and to maintaining the stoichiometric ratio. There are a number of methods of measuring the regression rate which are reviewed within. Current methods often require expensive specialist equipment which is out of the reach of the average researcher. Can a suitably accurate measurement technique be developed at a reasonable cost? Both ultrasound and the use of cameras are presented as viable techniques comparing in magnitude to the error associated with current techniques.

1. Introduction

A fundamental parameter that influences hybrid rocket design is the regression rate. It is the rate at which the solid phase propellant (the fuel grain) is converted into gas and key to understanding the rockets theoretical performance [1]. An alternative way to imagine it is that as the fuel burns the surface recedes. It is the rate at which this happens that is of interest.

Much of the research into hybrid rocket technologies is carried out using laboratory scale hybrid rockets. Usually, these are smaller scale hybrid rockets that are highly instrumented which their combustions chambers mounted securely and horizontally to a test rig. The current methods of measuring the regression rate are expensive and are out of the reach of the average researcher. Is it possible to develop a simple, reliable and cost effective technique to measure the regression rate instantaneously through non-intrusive means whilst providing suitably accurate results? This technical essay aims to react to this question whilst presenting the motivations to research hybrid rocket technology, understanding the regression rate and the need to measure it whilst presenting varying measurement techniques.

2. Hybrid Rockets

Hybrid rockets have been under development for a number of decades. Recently there has been resurgence in research as new technology has become available. Hybrid rockets generate thrust through combustion, a chemical process in which a fuel reacts rapidly with an oxidizer to produce a rapid expansion of heated exhausted gases to generate thrust [2]. Solid rockets have a combined solid state oxidizer and fuel within the combustion chamber, see Figure 1. Once ignited the rate of combustion cannot be controlled or extinguished [2]. In liquid rockets both the oxidizer and fuel are liquids. The correct ratio of oxidizer and fuel is pumped into the combustion chamber and ignited. The rate of combustion can be controlled by regulating the oxidizer and fuel flow [2]. Hybrid rockets, however, either have a liquid fuel and a solid oxidizer or, classically, a solid fuel and a liquid oxidizer. The solid fuel is stored within the combustion chamber, as in a solid state rocket, and the liquid oxidizer is stored separately and its flow may be regulated [2]. Hybrid rockets have a number of benefits as a launch system [2];

- The fuel is inert and so can be manufactured, transported, and handled safely with an unplanned ignition is not being possible as the propellants are physically separated.
- There is a greater selection of possible propellant combinations and additives such as energetic metals to improve thrust performance.

- The fuel grain is not a composite of the fuel and oxidizer, cracks that may occur within the fuel grain are not catastrophic as burning only occurs along the port.
- The need to pump only one fluid reduces the risk of a system failure, reduced manufacturing costs and reduces the weight of the overall system which can now be used for greater payload capacity and/or fuel.
- The regression rate is barely affected by temperature and so ambient launch conditions have little effect on the operating chamber pressure and hybrid technologies allow larger tolerances whilst remaining safe, reliable and providing the required launch performances and profile.

There are however a number of challenges when designing hybrid rockets [2];

- The regression rate is often low and therefore multiple ports are needed to obtain the required thrust performance resulting in a low bulk density and consequently a larger rocket.
- Combustion efficiency is typically 1-2% lower than for solid or liquid rockets.
- The ignition transient and throttle response is much slower than within liquid rockets.

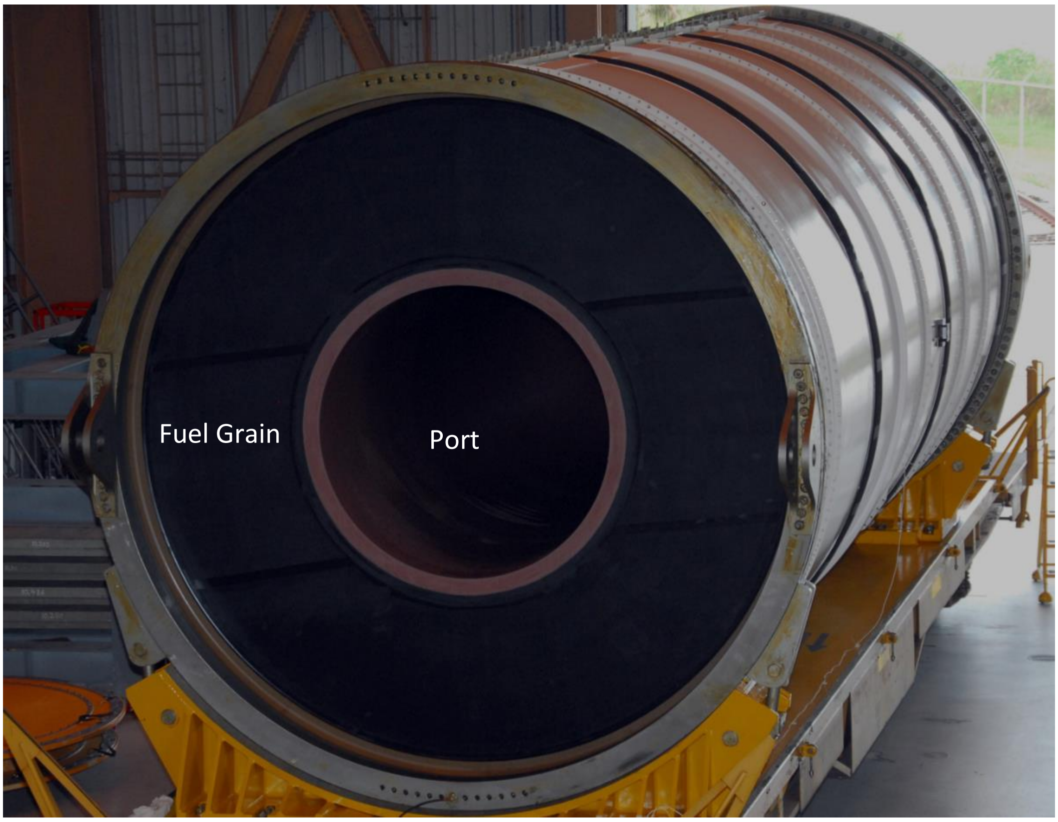

FIGURE 1: EDITED IMAGE OF A SEGMENT OF THE SOLID FUEL ROCKET BOOSTER [3]

3. The Importance of Regression Rate

There are three key reasons to know the regression rate; 1) To understand the thrust performance, 2) To understand the low regression rates experienced in hybrid rockets, and 3) To maintain the stoichiometric ratio.

Knowing the regression rate at a given moment means the unit of material that is available for combustion is known. Specific impulse is the change in momentum per unit of fuel. Through knowing the specific impulse of a fuel and the rate at which it is available to be combusted it is possible to determine the theoretical thrust performance of a hybrid rocket. This must be known in order to control and tailor the acceleration of the launch system to meet launch requirements. The geometry of the fuel grain can be shaped as to expose varying expanses of surface area. More surface area results in more fuel available for combustion and therefore greater possible thrust.

The solid propellant of a hybrid rocket is known to regress much more slowly as compared to a solid state rocket. Consequently, a much larger surface area is required to generate the required thrust. More research is needed to be undertaken to overcome this design challenge [2].

If one considers a circular port, as the fuel regresses more fuel is exposed for combustion. If the oxidizer ration where to remain the combustion efficiency would be dramatically reduced as the oxidizer ration shifts. In order to maintain the combustion efficiency, the correct ratio of fuel and oxidizer (known as the stoichiometric ratio) must be maintained. It is through knowing the regression rate the quantity of oxidizer required at a given point can be predicted and supplied [2].

4. Combustion

The regression rate is a mechanism of the combustion process and so it is important to understand the mechanics behind it. In hybrids rockets combustion occurs in the boundary layer above the fuel surface, see Figure 2. Shortly after ignition a chemically reacting boundary layer forms containing a diffusive flame region near to the surface of the fuel grain. The boundary is assumed to be turbulent and is characterised by strong velocities, temperatures and species gradients normal to the surface [2] [4].

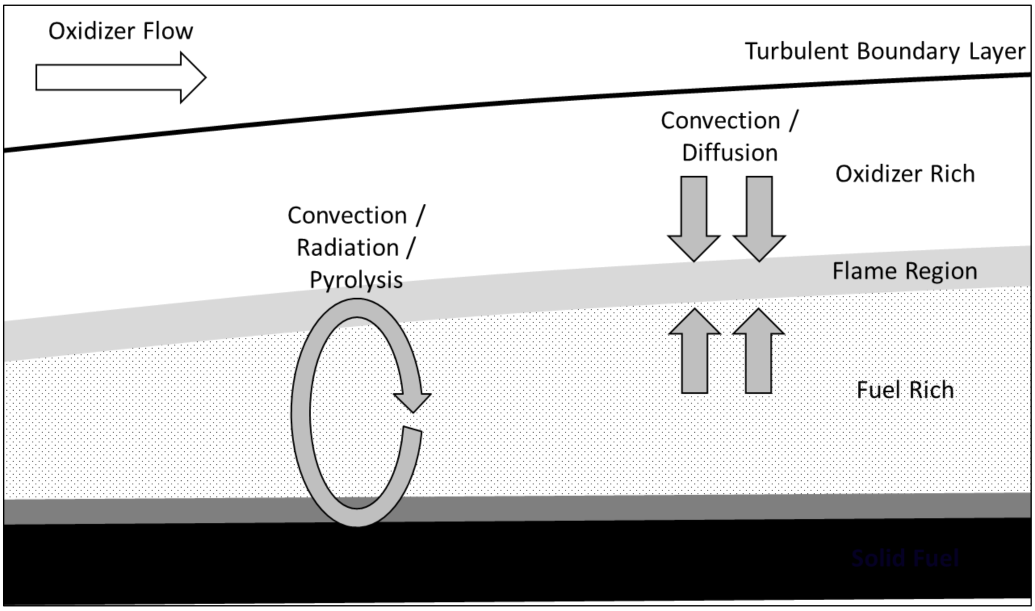

FIGURE 2: DEPICTION OF THE COMBUSTION PROCESS

Heat from the flames is convected and radiated to the fuel surface causing the solid fuel to pyrolyze. This pyrolyzed fuel vapour is transported to the flame zone through convection and diffusion, and mixes with the gaseous oxidizer which has been transported through the boundary layer from the core flow via turbulent diffusion. This mixture reacts and provides heat to sustain further fuel pyrolysis [2].

5. Peering Inside

There are a number of techniques that can be employed to measure the regression rate. This section will briefly consider the following; the stop/start technique, the use of resistors within the fuel grain, using ultrasound, the use of microwaves, two X-Ray techniques, and using cameras with post processing.

The stop/start technique is the simplest. The fuel grain is ignited and then extinguished after a desired burn period. Once the chamber is cooled, the fuel grain can be extracted for inspection and its thickness measured. This procedure is carried out over a number of test runs at varying burn durations to form a profile of the regression rate. This simplistic approach introduces a number of errors as it is not possible to extinguish the combustion process instantaneously. Additionally, the accuracy of the regression rate profile will depend on the discrete number of test runs and measurements recorded. This technique is time consuming and the regression rate is not measured instantaneously, instantaneous measurement is desirable.

In order to provide instantaneous results, a resistor ladder is embedded into the fuel grain. This maybe in the form of a single strip of material or a number of resistors wired such to be a “ladder”. As the fuel grain regresses, the resistors become exposed and are destroyed in the combustion process [5]. Through ohms law, this reduction in resistance, once calibrated, can be used as a method of determining the regression rate with much greater accuracy. However, it can be challenging to embed the resistors into the fuel grain whilst ensuring they are orientated correctly. Additionally, adding anything to the fuel grain can affect how it burns within the locality.

It is desirable for any measurement technique to be both instantaneous and non-intrusive. The following methods are example of such techniques. Mounted onto the chamber, an ultrasonic transducer maybe used to emit an acoustic wave which travels through the tested material which reflects on the regressing surface and received by the transducer. The time taken between the initial pulse and the reception of the reflected wave can be related to the material’s thickness [5]. An important consideration when using this technique is pressure and temperature as the speed of sound varies with both [6]. This is a favourable technique as it is cost effective, provides accurate measurement within ±0.3% and can more often or not be retrospectively fitted to existing laboratory scale applications [5] [7].

A microwave source can be used to create electromagnetic waves which reflect on the regressing surface. The phase of the reflected signal changes and the reflected signal is then compared with a portion of the transmitted signal to obtain regression rate information. The phase angle between the incident and reflected signal shifts with the reduction in length of the regressing sample and the regression rate is directly proportional to the rate of change of this phase shift [5]. This method consistently provides good results within ±4.2% [8]; however, it does have reasonably high set up costs.

X-ray technology provides two possible techniques. Firstly, x-radiation is attenuated in proportion to the thickness and physicochemical properties of the material. Assuming a linear relationship, the extent of attenuation can be related to the thickness of the fuel grain [5]. Secondly, real time radiography can be employed. The profile of transmitted radiation has a sharp gradient at the position corresponding to the solid to gas interface. The x-rays are converted into visible light which is captured using a camera. Imaging processing software is then used to determine the regressing surface and measure the regression rate [5]. Both of these techniques are extremely hazardous, are expensive and provide accuracy up to ±3.5% [9].

Final camera maybe used to capture the event with imaging processing software used to determine the regression rate [5]. As discussed in the combustion process, the flame region sits off the fuel surface and so in fact one is measuring the change in position of the flame region. This technique can be undertaken without considerable set up costs although the reliability of the method must always be questioned and it is necessary to ensure the boundary has been defined correctly.

6. Peering Inside – Low Cost Approach

Through having a clear set of requirements and from understanding the principles behind each of the measurement techniques it is possible to determine a route to developing an appropriate low cost solution. Often there is a tendency to over engineer a solution and in particular to seek greater accuracy when it is not required at additional cost. Ultrasound and use of a camera with video processing software both seemed viable techniques to investigate as they provided accurate result and could be undertaken without using high end specialist equipment.

When employing the ultrasonic technique high end transducers are often used with specialist software which is extremely expensive. Consideration was made to understand if would be possible to create a similar set up at a reduced cost through using existing equipment. A pulse-receiver would be used to generate a signal via a transducer, amplifying the return signal and processing this data to provide meaningful results on a computer via a data acquisition card. The greatest challenge in this set up is the selection of an appropriate transducer as these are specialised for the appropriate frequency, amplitude, and required diameter and head shape. To determine this there are a number of considerations;

Beam divergence is the spread of the signal as it leaves the transducer head resulting in a reduction in amplitude. This has a direct relationship between the frequency transducer head size and the thickness of the specimen [10]. If the amplitude of the signal reduces too much, the transducer will not be able to detect the return signal. An appropriate frequency should therefore be selected.

As a sound is transmitted through a medium its intensity decreases with distance due to “scattering” and “absorption”. The former is the reflection of sound in all directions and the latter is the conversion of sound energy into other forms of energy such as heat [10]. The combined effect is known as attenuation.

As a sound wave transitions through two different densities of material only a portion of the energy is transitions through with the rest being reflected; this is known as acoustic impedance [10]. A larger disparity in the density results in a greater acoustic impedance. In this application, there are density changes between the transducer head and the chamber, between the chamber and the fuel grain and the fuel grain edge that is regressing and the same on the return. As it is the final stage that is of interest, sufficient energy must be provided to ensure the return signal is strong enough to be detected. Between each layer, it is possible for an air gap to be present which results in another transitional layer. To reduce the effect of this, a couplent (a gel or a fluid) is placed between to reduce the density disparity [11].

Finally, acoustic waves will reflect off any discontinuity in material, such as a crack or pitting, but for such a discontinuity to be detected the feature must be larger than one-half of the wavelength of the acoustic wave. Consequently, because such detection will only occur with a higher frequency, in order to not pick up these features the frequency should be as low as possible [10].

It was calculated that a either a 25 mm diameter transducer with a frequency of 0.555 MHz or 12.5 mm diameter transducer with a frequency of 1.66 MHz would be sufficient. This compared justifiably with apparatus used in reviewed research papers. A suitable transducer could be bought off-the-shelf for £250. It was found that the greatest challenge would be detecting the appropriate return signal as calculations showed that only 2.2% of the excitation energy would be received [12]. Unfortunately, a transducer could not be procured in time to conduct a test run.

Slow motion cameras can be used to record footage of the fuel grain regressing and post processing undertaken to calculate the regression rate. The camera is the largest to contribution to accuracy and cost. A video is made up of a number of still images, or frames, which are played together at a certain frame rate to give the illusion of fluid motion [12]. The frame rate is the number of frames per second. A greater frame rate would provide more discrete points for measurement. To capture and image, light entering a camera hits an image sensor that consists of a 2D array of cells known as pixels. The sensor measures the amount of incidental light that is hitting each pixel and converts this into a voltage and subsequently into a digital number [12]. The greater the number of pixels within the 2D array the more detail can be captured. This is described as the camera's resolution. Research papers showed that typically slow motion cameras are used filming at high frame rates and at high resolution.

A test recording was made comprising of a black card moving across a white background to simulate the regression rate using a camera filming at 24 fps with a resolution of 1280 x 720. MatLAB was used to write a script to acquire the video frame by frame, convert it to greyscale prior to converting it into a binary image and either to calculate the area of the white region before working out its difference to calculate the regression rate or to locate and track an arbitrary boundary between the light and dark regions.

Through experimentation of both methods it was found that the former approach yielded a measurement accuracy of ±3.83%. This compared with the accuracy of previously mentioned measurement techniques, however, it was found to be difficult to develop a script to accurately define a boundary and it produced an error of ±6.92% [12].

7. Summary

Hybrid rockets classically consist of a liquid oxidizer stored separately and solid fuel within the combustion chamber known as the fuel grain. This system provides a number of benefits. They are much safer than solid state rockets and liquid state rockets, offer a larger selection of propellant choices, can cope with a greater range of tolerances, and are less mechanical complex than liquid rockets. As with any system, there are also a number of disadvantages, a predominate issue being the low bulk density due to the need of multiple ports to expose enough surface area to provide the required thrust performance.

The regression rate, the rate at which the fuel grain is pyrolyzed, is a fundamental parameter key to understanding the thrust performance, the low regression rates experienced in hybrid rockets, and to maintaining the stoichiometric ratio. The combustion process itself takes place in a flame region away from the surface of the fuel grain. This is a unique characteristic of hybrid rockets.

A number of techniques have been described to illustrate the benefit of being able to measure instantaneously and non-intrusive. Ranging from the stop/start technique to measure the fuel grain physically and specific points which prevents continuous test runs, embedding a resister ladder to obtain instantaneous measurement but causing inefficiencies with the combustion process or using ultrasound to use sound waves to reflect off the regressing fuel grain surface to measure the regression rate. Further techniques mentioned are through using X-ray technology, microwaves and using cameras to track the regressing surface.

Currently, these techniques are undertaken using specialist equipment at great expensive or are hazardous. Ultrasound and using cameras was identified as possible means of creating a low cost means of measuring the regression rate. Theoretically it was proven that the return signal pulse-receiver generating a signal via a transducer could be used to measure the regressing surface. Additionally, a video camera could be used to track the regressing surface using a MatLAB script. Both techniques provided the same order of magnitude error as with existing higher end techniques. Work is still required as test using on a laboratory scale hybrid rocket to verify the techniques have not been conducted.

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