IMAGING COMBUSTION IN HYBRID ROCKET ENGINES

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[1] INTRODUCTION

In recent years, Atout Process Limited has successfully applied Electrical Capacitance Tomography (ECT) technology to solve a variety of long standing technical problems in the space sector [1,2,3]. An instance is in 2018 during a partnership with Kingston University, where combustion in a bi-propellant rocket engine was imaged using this technique [3]. Continuing this research, Kingston University and Atout Process Limited partnered again with the aim of imaging combustion in hybrid propellant engines.

Why?

Hybrid propellant rocket engines have seen a resurgence of use due to its safety, storability, controllability and cost effect nature as opposed to solid or liquid engines [4]. Calculation of their regression rate is challenging due to dynamic factors unique to each firing of the engine.

The methods currently utilised to examine the grain to determine the regression rate suffer from being post combustion, static and invasive. ECTs were chosen as it offers live data capture during combustion which is dynamic, non-invasive and has a high temporal resolution.

What is ECT?

ECT is an imaging technique to inspect dielectric permittivity distribution [5]. Figure 1 shows a typical setup of the sensor which works by arranging a set of electrodes around the subject. The electrodes are sequentially charged whilst simultaneously measuring the capacitance developed in uncharged electrodes [6]. Tomographs which show the dielectric permittivity distribution are then reconstructed, such that variations in the permittivity can be correlated to physical phenomena.

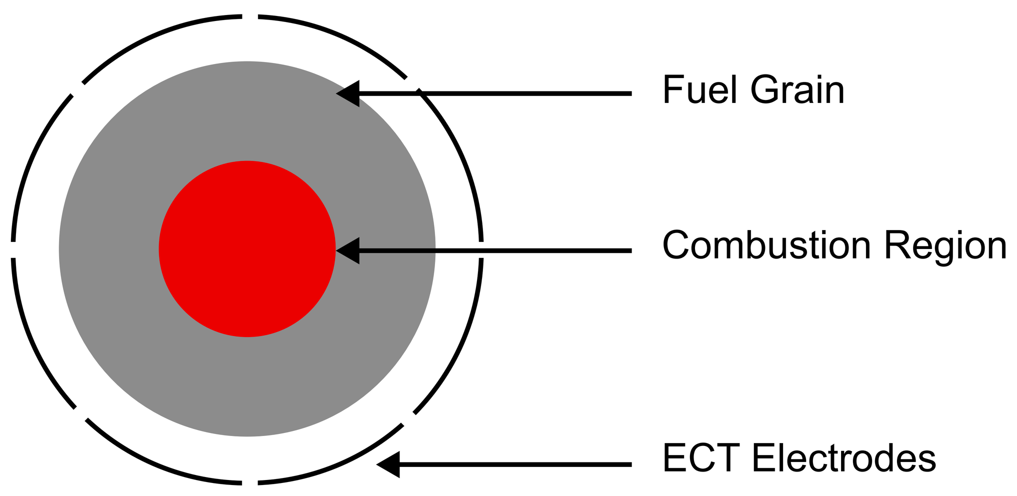


Figure 1:

Demonstrates the arrangement of the electrodes of an 8 electrode ECT sensor around a combusting hybrid rocket engine fuel grain

The practical application of ECTs to a hybrid rocket engine is shown in Figure 2 where the results presented in this poster are from this setup and test fire shown.

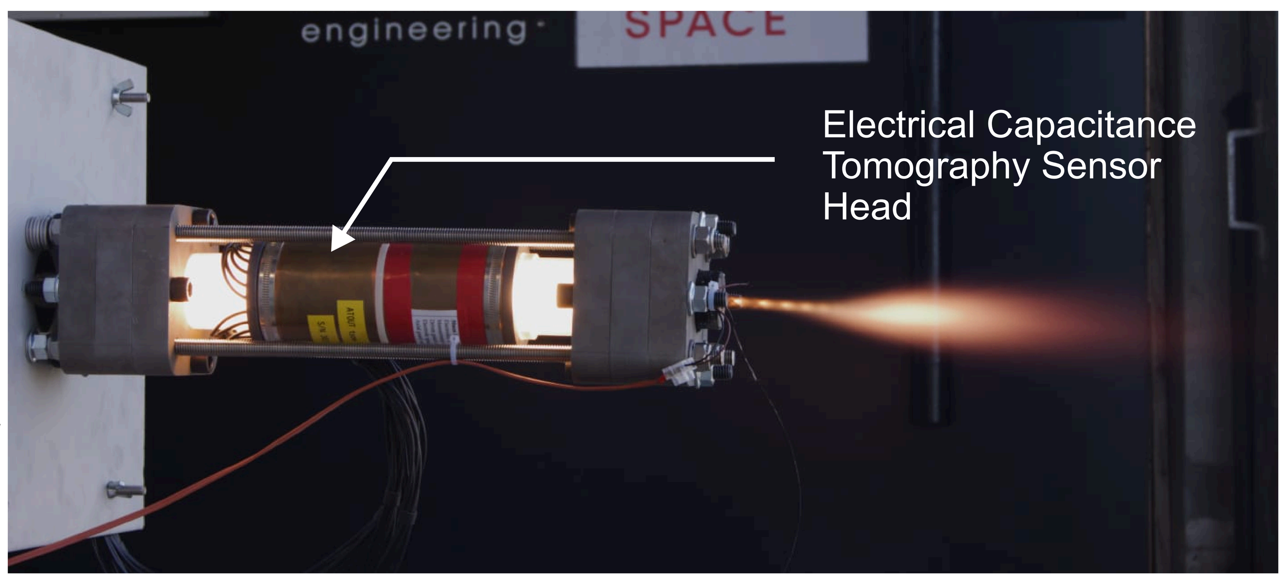


Figure 2:

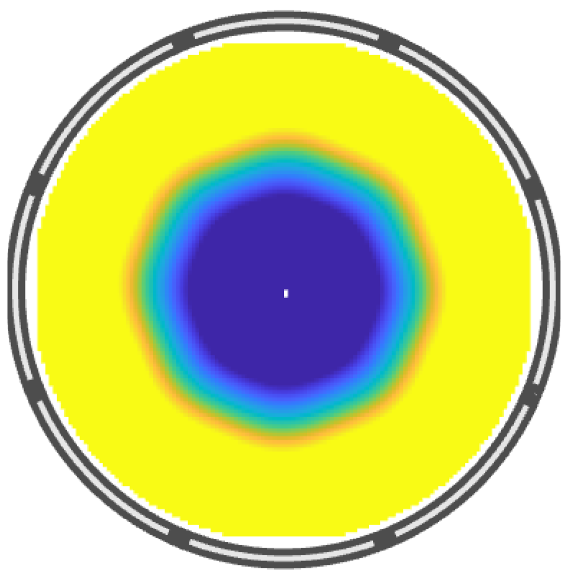
Shows the hybrid rocket engine named MACAW firing with an ECT sensor from Atout Process Limited capturing data simultaneously.

[2] RESULTS

The results presented in Figures 3 and 4 are from our initial set of captured datasets using the Nitrous Oxide and Acrylic hybrid propellant rocket engine shown in Figure 2 which aimed to determine the suitability of using ECTs for this application.

Varying the permittivity ratio used in the reconstruction process resulted in 2 distinct types of tomographs which we have given the names Combustion Centric Tomographs (CCT) and Grain Centric Tomographs (GCT) as shown in Figure 3.

In the images of the CCT and GCT below they have been taken at the same time stamp, however, due to ongoing investigations and formation of the analysis software there is significantly more averaging of features in the CCTs than in the GCTs.This leads to a disparity in their geometric features, although trends can still be extrapolated. Future research will harness machine learning algorithms to resolve this issue.



Combustion Centric Tomograph:

This tomograph, which has a permittivity ratio greater than one, allows for analysis of the unburnt grain, the burning region and the central port. These tomographs have a lesser response to dynamic combustion phenomena than GCTs. This is attributed to a complex response from the materials to excitation by the electric field. We hypothesise that the yellow to orange to green region correlates to the changing of the propellant grain phase from solid to molten and then gaseous state. We further hypothesise that the transition from green to dark blue is the reduction in density of the non-ionised gaseous propellant to ionised plasma found in the centre of the combustion zone.

Grain Centric Tomograph:

This tomograph, which has a permittivity ratio less than one, allows for analysis of propellant grain heating due to the passage of combustion gases. This was confirmed by examining the shape of the yellow region with respect to the shape of the grain's port in destructive post combustion chamber analysis. Over the duration of the hot fire, there was a notable response of these tomographs to changes in the oxidiser inlet pressure.

Figure 3: Shows the two types of tomographs, Combustion Centric Tomograph (top) and Grain Centric Tomographs (bottom).

Using the Grain Centric style of tomographs, the horizontal midline of permittivities was plotted over time as shown in Figure 4. These maps allows for inspection of changes in the permittivity over the duration of the hotfire such that different distributions are correlated with different modes of operation.

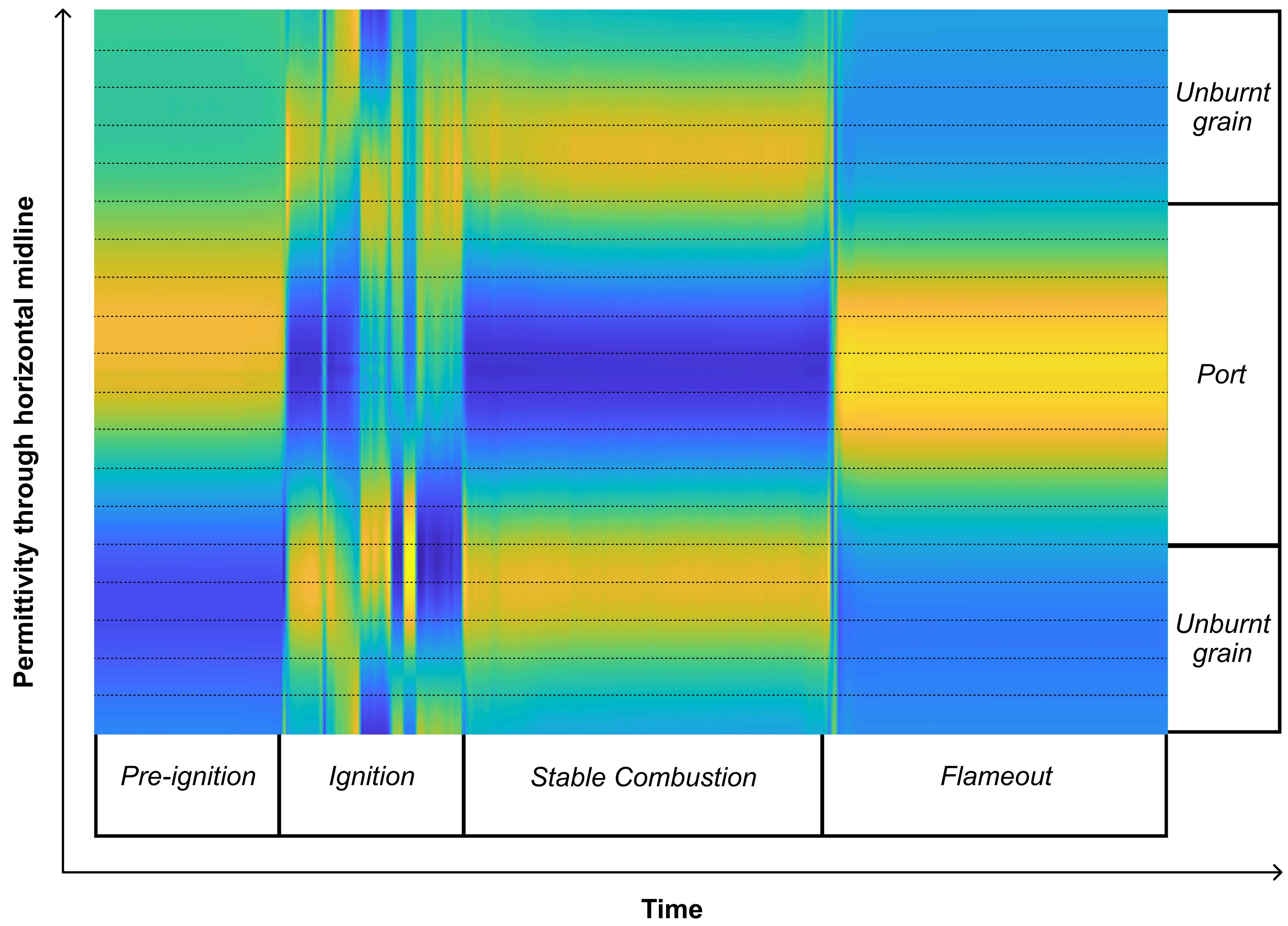


Figure 4: Shows the normalised permittivity over a horizontal midline of a GCT over time where various stages engine operation is highlighted as well as different regions of the grain. Dashed lines at equal intervals are also provided for examination of changes distribution of the various permittivity regions.

The distribution of permittivities over time show two distinct distributions: normal and bi-modal which correlate to no combustion and stable combustion respectively. Therefore, for a live application of ECTs to hybrids, the number of peaks occurring along the midline can indicate the state of combustion. Moreover, determining the sharpness of these peaks in a bi-modal distribution over time will indicate stability of the combustion.

Further from this, examining the distribution of the different regions of permittivity before and after combustion, it can be noted that the location of the permittivity band correlating to the port changed. Physically this was not the case and therefore can be attributed to the assumptions, errors and simplistic reconstruction method used to create the tomographs. Future work will aim to improve this where the authors hypothesise changes in the port geometry can be inspected using this technique.

[3] IMPACT

The application of ECT imaging to hybrid rocket engines holds considerable advantages for their utilisation across diverse scenarios. The capability to dynamically monitor the propellant grain during engine operation is poised to enhance both safety and efficiency, rendering hybrid systems more conducive to manned missions while concurrently reducing associated costs.

Beyond operational considerations, ECT technology presents a valuable application in the realm of quality assurance. Its deployment in scrutinising the propellant grain during the manufacturing phase serves to preclude catastrophic failures by identifying defects in a preemptive manner. Furthermore, this technology extends its utility to the examination of components beyond the fuel grain, encompassing critical elements such as propellant lines.

An additional notable hypothesis by the authors is the obviation of direct thrust measurements as thrust can be determined through correlation of the permittivity readings with the nozzle dimensions.

[4] NEXT STEPS

At the current time, the application of ECT technology to the field of rocketry is in its infancy with only a limited number of studies on the niche. For further and refined applications several steps need to be taken which all fall under developing a deeper understanding of tomographs to physical phenomena. The first step toward this is refinement and tailoring of the data collection and reconstruction processes for this specific application. The latter can be done through 2 avenues primarily: numerical algorithms and machine learning algorithms. The effect of pressure and temperature on the permittivity values for different pairs of propellants also need to be determined.

These steps will lead to refined tomographs which will lead to better correlations to physical phenomena occurring during the combustion process

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