MACAW - II

Monitoring Hybrid Grain Regression Using ECT

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1. Introduction

Electrical Capacitance Tomography (ECT) has been applied to the problem of directly imaging combustion in both bipropellant and hybrid rocket engines [1]. A partnership between Kingston University and Atout Process Ltd continues to yield methodologies for monitoring internal characteristics of rocket engines, with recent results showcasing the capabilities of ECT to monitor the regression of a hybrid engine fuel grain.

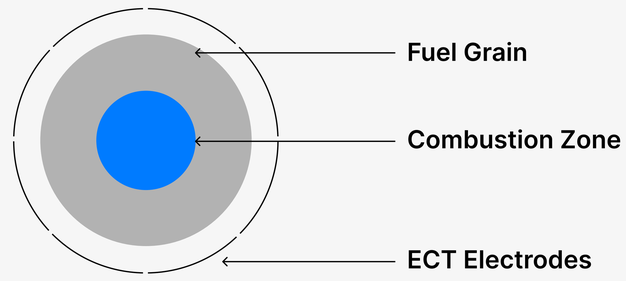

Figure 1: *Demonstrates the arrangement of the electrodes of an ECT sensor array around a combusting hybrid rocket engine fuel grain*

ECT Overview

ECT is an imaging technique currently applied to various industrial processes [2, 3, 4].

- An array of electrodes surrounds the imaging domain, as shown in Figure 1.
- A voltage is applied to a 'source' electrode. Capacitance values between this electrode and the remaining electrodes are measured. This process repeats until capacitances between all electrode pairs are measured.
- The capacitance measurements are used to construct an image displaying the distribution of dielectric permittivities within the imaging domain.
- **Variations in the constructed permittivity distribution correlate to physical phenomena.**

Figure 2 shows the ECT sensor array being calibrated for use, while Figure 3 shows the array capturing data during a nylon/gaseous oxygen (GOx) firing of the MACAW-II hybrid rocket engine.

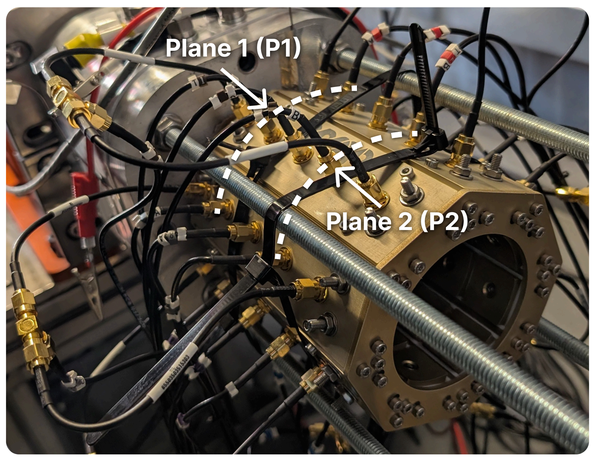

Figure 2: *ECT sensor array from Atout Process Ltd during calibration - prior to insertion of grain. Locations of Plane 1 (P1) and Plane 2 (P2) are shown*

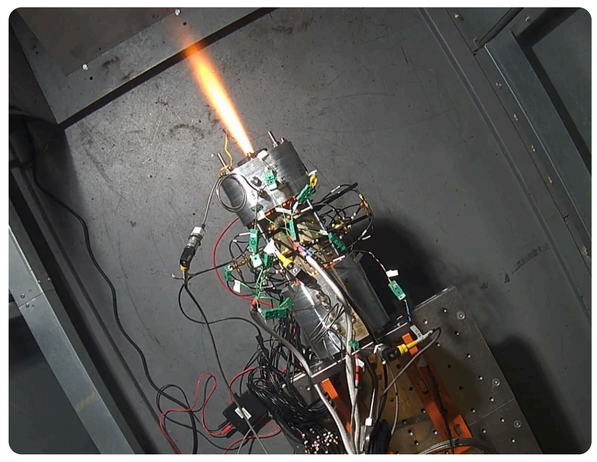

Figure 3: *The ECT system capturing regression data during a test firing of a nylon grain with gaseous oxygen in the MACAW-II thruster*

Motivation

Despite the field of hybrid rocket engines gaining traction in recent years due to their simplicity, safety and controllability, persistent issues remain [5]. One key issue is the **difficulty in determining the regression rate during burns.**

ECT is non-invasive, non-intrusive and exhibits high temporal resolution. These attributes highlight **ECT as a valuable technique that can be deployed to dynamically monitor regression rates in multiple planes along the fuel grain.**

2. Results

Figure 4 displays examples of the tomographs that make up the dataset. Analysis using image processing software 'ImageJ' was carried out on 14 frames obtained during stable combustion, spaced out in 1 second increments. Figure 5 shows how the scale for regression measurement was obtained.

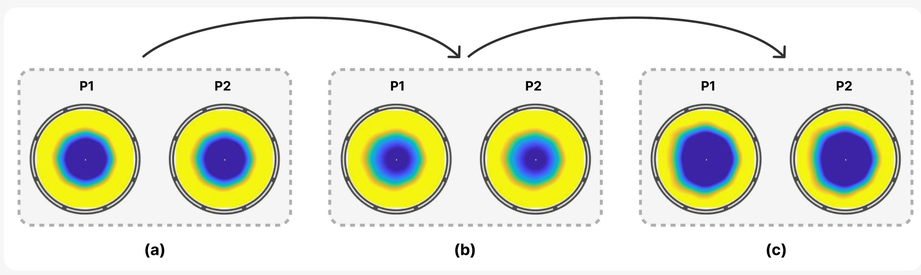

Figure 4: *Examples of obtained tomographs. (a) initial grain; (b) during oxidiser flow (pre-ignition); (c) 6 seconds into the burn. Evidence of fuel grain regression is clear when comparing (a) and (c)*

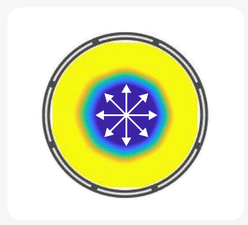

Figure 5: *Calibration measurements yielding a scale of 2.43 pixels/mm*

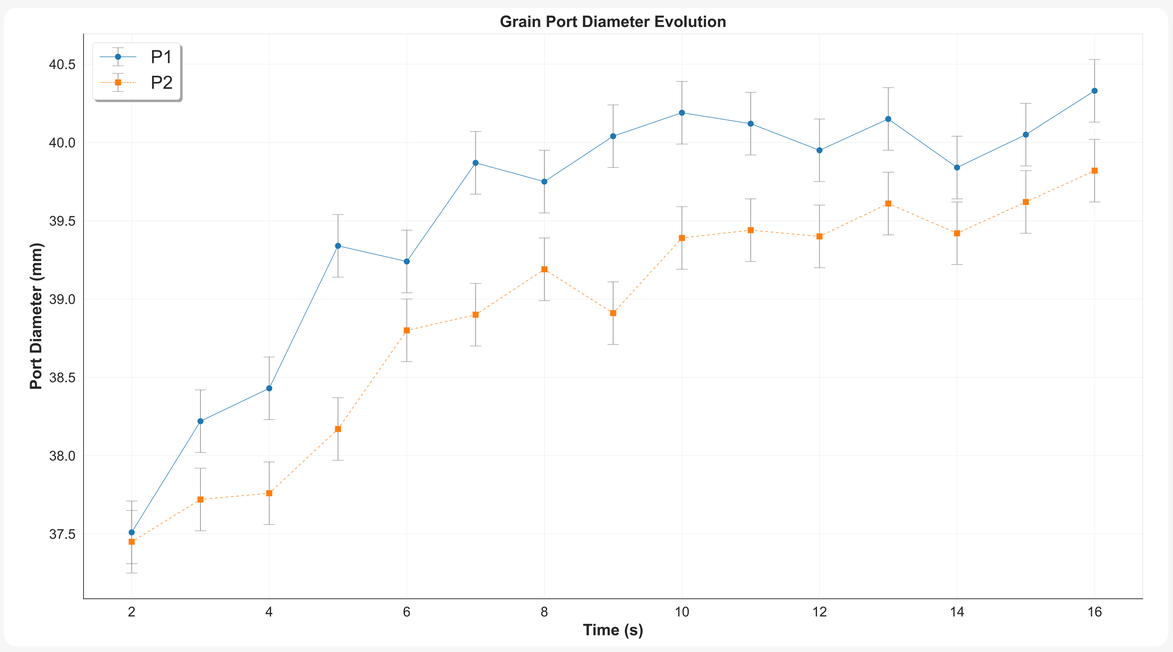

Figure 6: *Plot displaying the growth of the port over time due to regression of the nylon grain starting two seconds after ignition. As expected, plane 1 displays more regression than plane 2 as it is closer to the injector*

During the initial ~2-second transient ignition phase, regression rates were significantly higher than the average rates across the burn. Regression rates of **3.76 mm/s at plane 1** and **3.73 mm/s at plane 2** were observed during this phase. Combustion subsequently stabilised into a steady state (t > 2 s). In this steady phase, the port diameter evolution is shown in Figure 6, with regression rates dropping to **0.20 mm/s at Plane 1** and **0.17 mm/s at plane 2**.

Figure 7 displays the complete port diameter history from ignition (t = 0 s), clearly highlighting the initial high-regression transient. This pronounced spike is likely the result of **excess heat flux combined with rapid melting of the exposed nylon fuel surface**. After this transient period, combustion transitions to the stable regime characterised by the lower, steady regression rates.

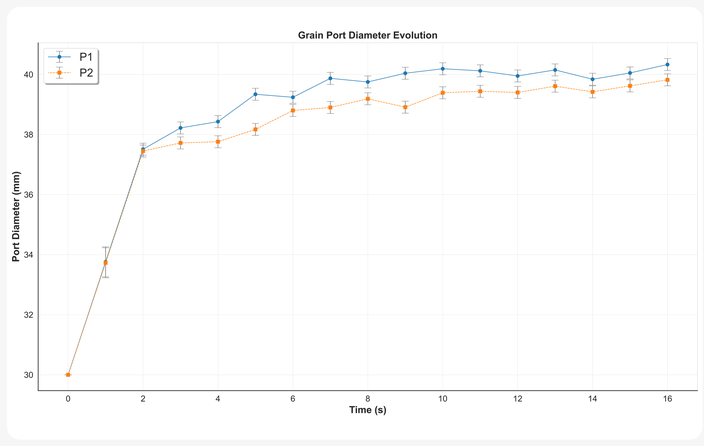

Figure 7: *Plot displaying the growth of the port diameter over time including the initial transient phase lasting approximately 2 seconds*

Figures 8 and 9 show, respectively, the physical port diameters for plane 1 and plane 2. **The port diameter in the region corresponding to plane 1 matches well with ECT data, showing a final port diameter of around 40 mm.** The port diameter for plane 2 was around 36 mm, differing from the ECT results. This is hypothesised to be the result of calibration drift or asymmetrical regression coupled with differences in plane 2's combustion environment.

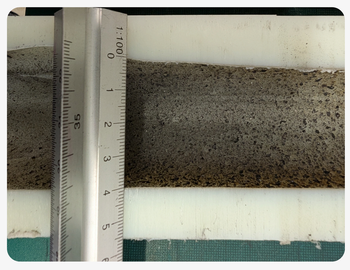

Figure 8: *Post-test physical measurement of port diameter for plane 1. The obtained value matches ECT data*

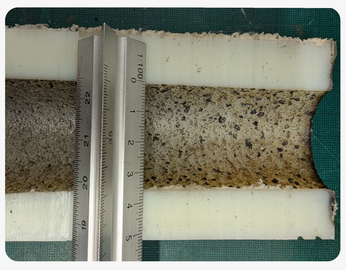

Figure 9: *Post-test physical measurement of port diameter for plane 2. The obtained value is lower than anticipated*

3. Impact

The application of ECT to **obtain direct measurements of the regression of a hybrid fuel grain** leads to a variety of capabilities. **Safety and efficiency can be enhanced** by monitoring the burn in real time.

- Regression measurements can enhance understanding of the link between regression rate dynamics and combustion instabilities, **aiding the development of more stable hybrid rocket engines.**
- Transient regression fluctuations that may precede combustion instabilities can be identified, enabling early warning strategies to **improve engine reliability.**
- Comparison of regression rates for differing propellant materials can offer **quantitative results on novel grain formulations.**
- Direct regression measurements can also be used to validate and refine CFD and combustion models, **improving predictive accuracy for hybrid rocket performance.**

For defence applications such as missile propulsion, ECT can serve as a valuable quality assurance asset by enabling non-destructive inspection of hybrid fuel grains for cracks and defects before deployment.

4. Next steps

The application of ECT to rocketry is a long way from reaching maturity. In order to achieve its full potential in this domain, **further data analysis and the refinement of image reconstruction techniques** need to be carried out.

The development of more sophisticated image reconstruction algorithms can enhance boundary layer resolution. **Boundary layer enhancement** is likely to offer insight into the multiphase nature of the combustion zone. The effects of temperature and pressure on the permittivity distribution are yet to be determined.

Measurement uncertainties introduced by the methodology can be minimised by implementing software to **automate the measurement process for each frame directly from capacitance measurements.** Moreover, this process would enhance the temporal resolution of the results and negate the requirement for image reconstruction - perhaps shedding light on the nature of the initial transient regression rates.

References

[1] - V. Williams, A. Puri, P. Shaw, A. Hunt & R. Foster-Turner (2024), 'Imaging Combustion in Hybrid Rocket Engines Using Electrical Capacitance Tomography', First International Symposium on Small Launch Vehicles and Spaceports, ESA Conference Facility, Harwell, UK.

[2] - A. Hunt, R. Foster-Turner & R. Drury (2018), 'Propellant slosh force and mass measurement'. International Journal of Aerospace Engineering, 2018

[3] - Li et al. (2023), 'Deep learning-based tomographic imaging of ECT for characterising particle distribution in circulating fluidised bed', AIChE 69, 5.

[4] - Hui et al. (2024) - 'Visualisation detection of moisture accumulation in asphalt materials using electrical capacitance tomography technology', Road Materials and Pavement Design

[5] - Glaser, Hijlkema & Anthoine (2023), 'Bridging the Technology Gap: Strategies for Hybrid Rocket Engines', Aerospace 2023, 10(10), 901.