Characterization of Hybrid Motor Thermal Penetration Depth with Ultrasonic Sensing

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Background

Hybrid Rocket Motors
- Chemical propulsion that utilizes a fuel and an oxidizer in two different phases, (usually liquid or gaseous oxidizer with solid fuel)
- Mechanically simple and can be throttled, shut down, and restarted
- Safer and more cost-efficient than conventional system liquid or solid propellants systems
- Small-scale hybrids can be subject to low combustion efficiency
- Link between theory and experimentation not explored, limiting their potential of being a leading candidate for propulsion solutions.

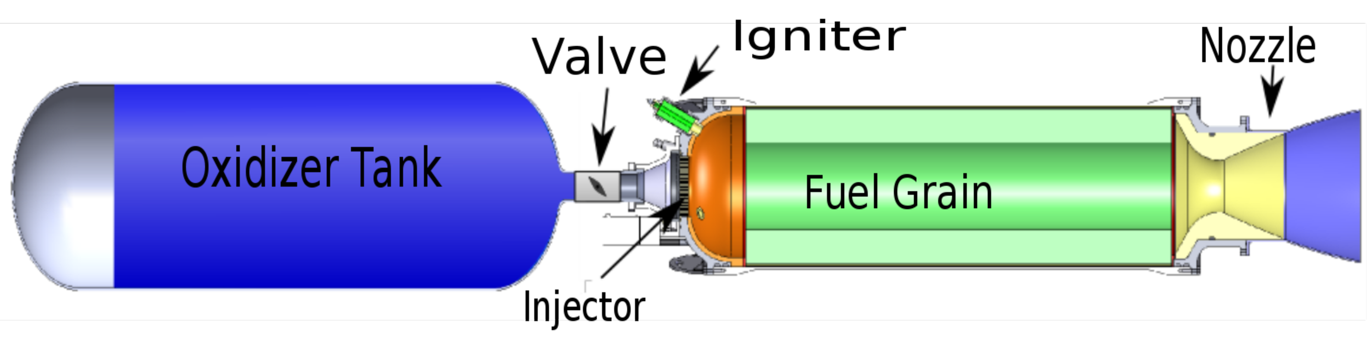


Figure 1: Schematic of a typical hybrid rocket motor

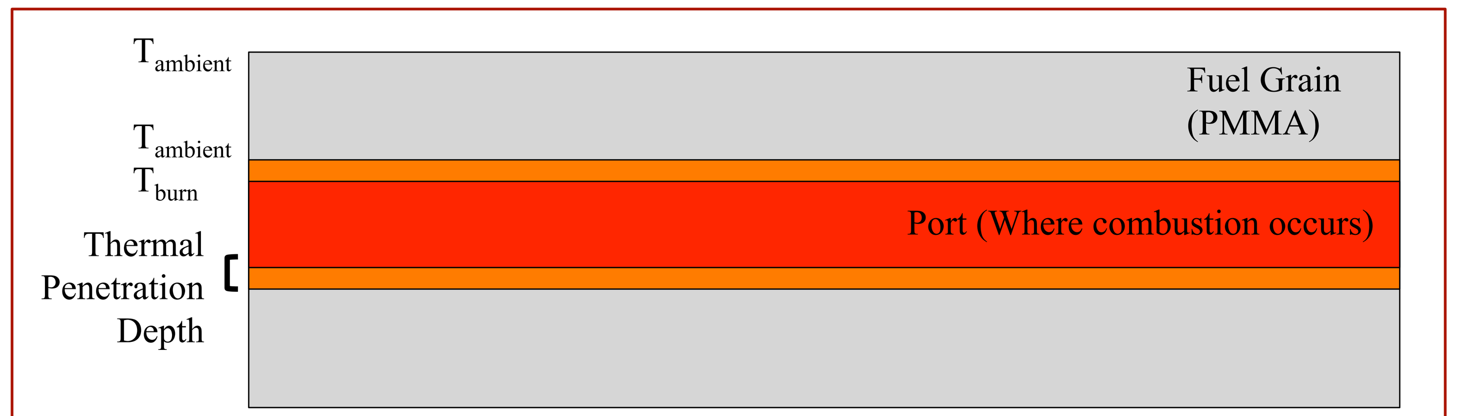


Figure 2: Thermal Penetration Depth in Fuel Grain

Goal

The goal of this study is to determine and characterize the thermal penetration depth (TPD) of a hybrid motor using Poly(methyl methacrylate), also known as PMMA or acrylic, as fuel.

Method

Ultrasonic waves vary with temperature and can be used during a hot fire without changing the setup of the motor

1. Measure thickness of fuel with ultrasound sensor
2. Calculate TPD from 4K video of motor burning transparent fuel
3. Find speed of sound in PMMA at high temperatures
4. Estimate average speed of sound and temperature profile in TPD from video and ultrasound

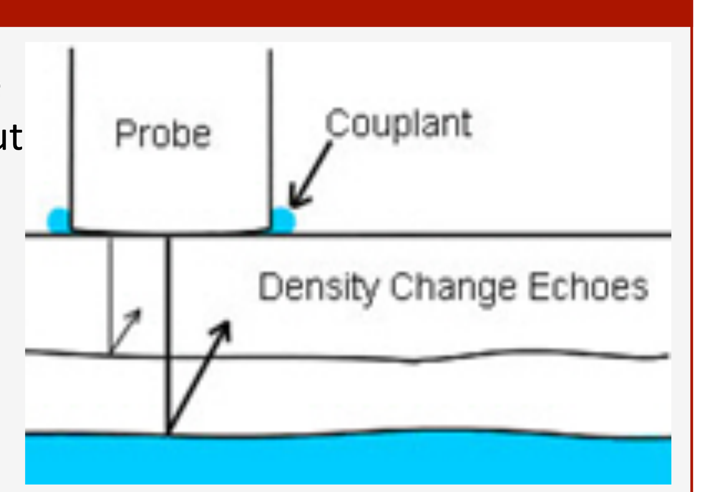


Figure 3: Pulse-Echo method for ultrasound

Ultrasound Data Collection

Used NDT Systems TG 410 Ultrasonic Thickness Gauge
- 1.25 MHz frequency
- Communicates over serial for 15Hz sampling data acquisition through LabView
- 3D printed holder on optical rail designed to keep transducer directly above port

Data Collected for 3 Hotfires on 0.5in port diameter duel grains:
- Hotfire 12 – 15s
- Hotfire 13 – 15s without nitrogen purge
- Hotfire 14 – 20s

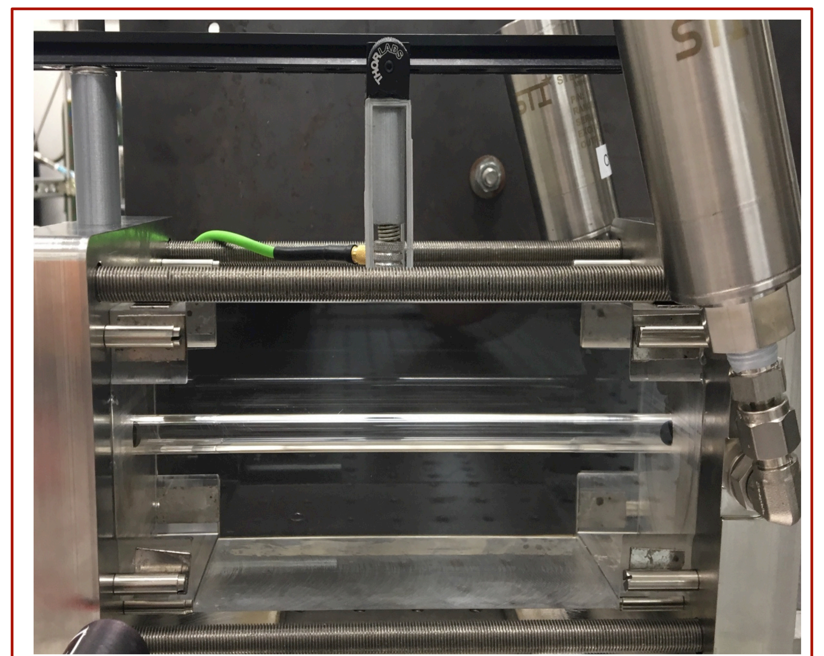


Figure 4: Ultrasound transducer and holder on fuel grain ready for a hotfire

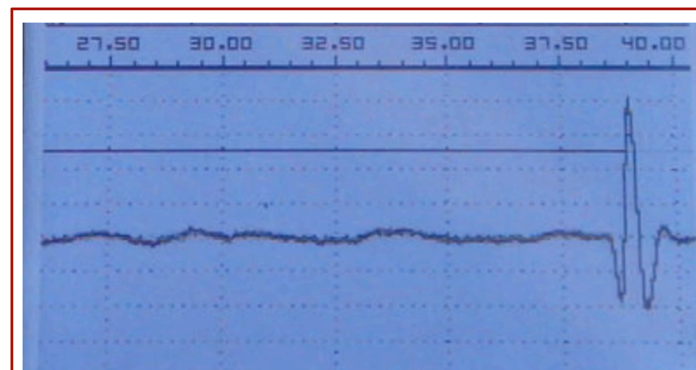


Figure 5 (top): Ultrasound thickness gauge screen pre-hotfire. There is one peak in the ultrasound waveform

Figure 6 (bottom): There are now two peaks in the ultrasound waveform, with the left one possibly from an echo off the TPD

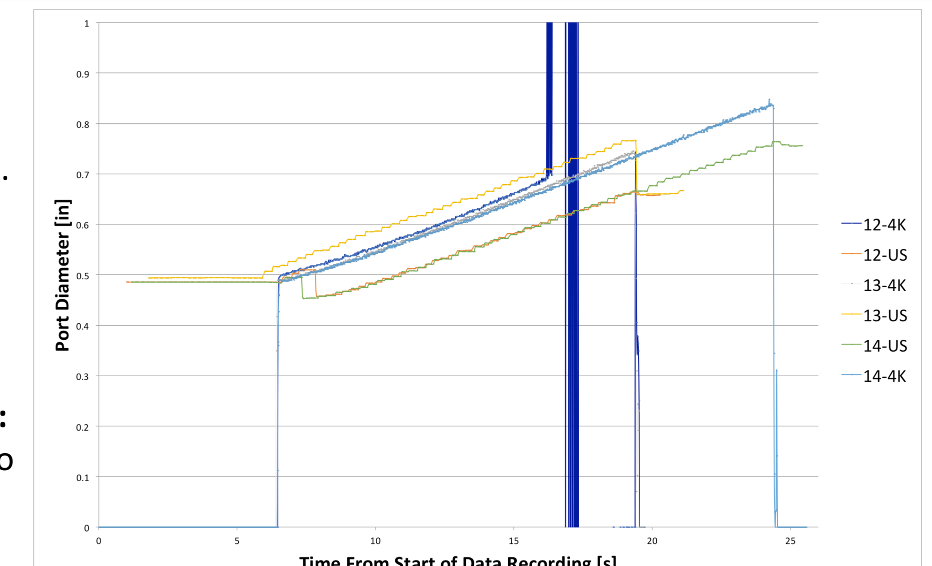


Figure 7: Comparison of ultrasound thickness values to 4K video thickness. They follow the same slope, with the leftmost wave peak (yellow) indicating a constant TPD

Thermal Penetration Depth

The TPD in the motor was calculated from a shadow layer around the port in the 4K video of the burn
- This layer is still present after the burn is over, but the second peak in the ultrasound waveform is not
- Some material change is present to create this optical change, but it may not be a permanent density change
- Comparing the TPD from the ultrasound and from the video yields what its average speed of sound is

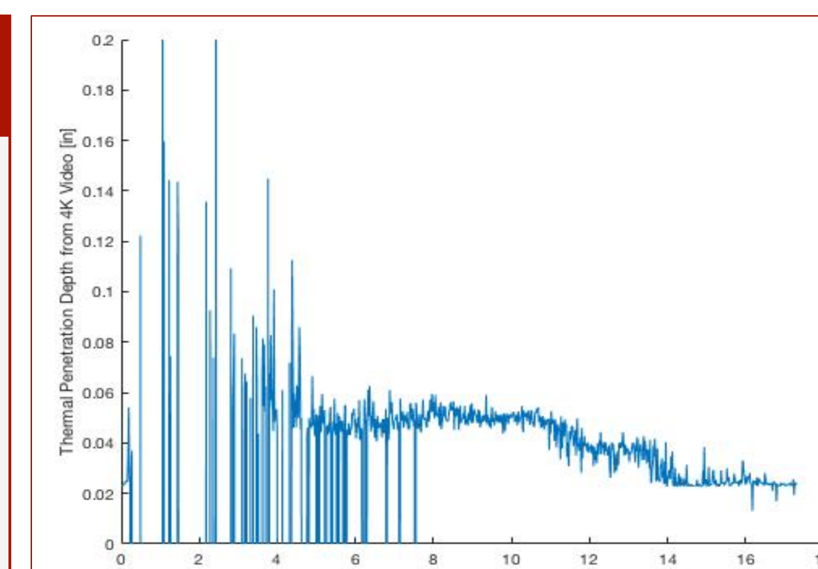


Figure 8: TPD from 4K video analysis

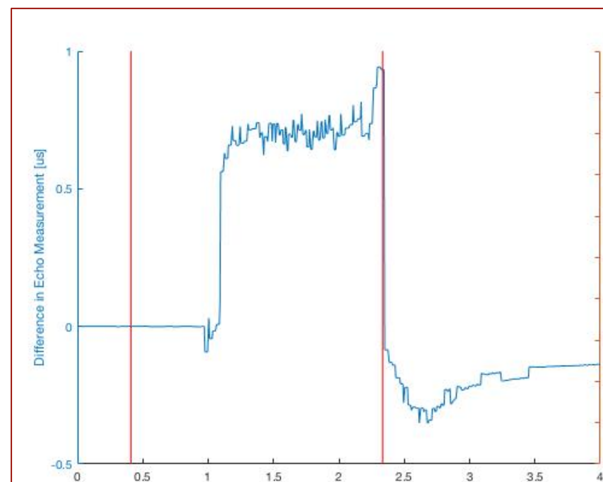


Figure 9 (left): Difference in ultrasound time measurements between left and right peak during the burn, indicative of TPD thickness

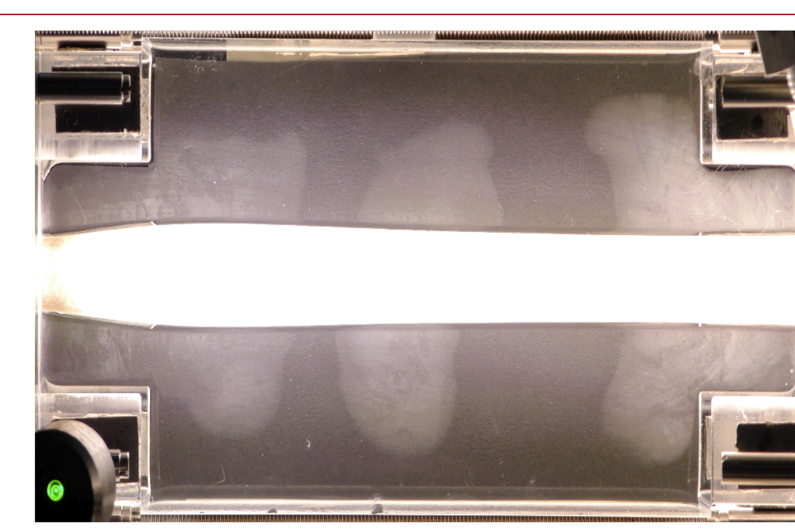


Figure 10: 4K video frame during hotfire. Shadow above and below port burning shows change in optical properties that remains after cooldown – could be TPD

Speed of Sound

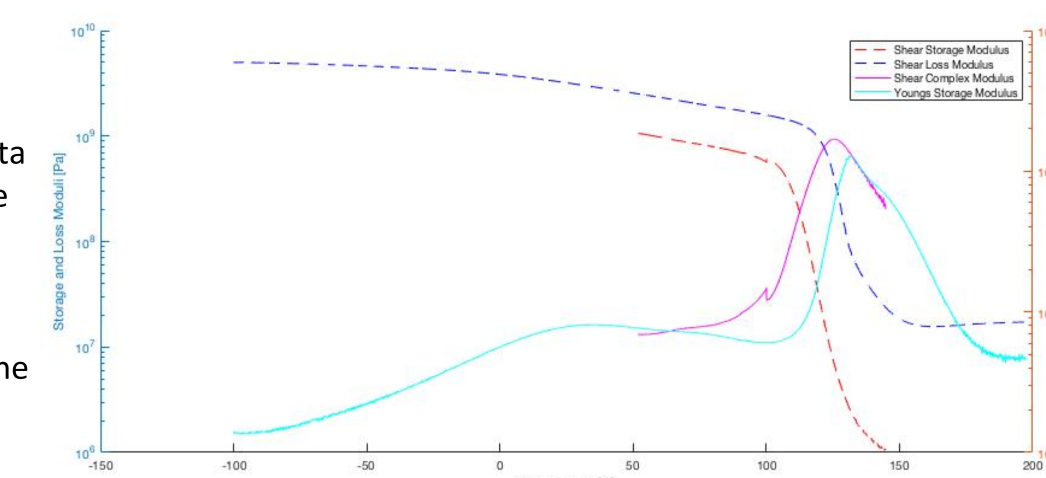
Speed of sound in an isotropic solid is given by the equations:

$$c_{\mathrm{solid,p}} = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}, \qquad \nu = \frac{E}{2G} - 1$$

Where E is the Young's Modulus, ν is the Poisson's Ratio, ρ is the density, and G is the Shear Modulus
- Shear modulus measured with an ARES G2 Rheometer
- Young's Modulus data from DMA analysis of team at JPL using slightly different PMMA
- Density treated as constant with temperature

	Literature Value (ambient)	Measured Value (ambient)
Shear Modulus	1.7 - 2.3 GPa	1.04 GPa
Young's Modulus	2.8 – 6.0 GPa	2.53 GPa
Poisson Ratio	0.32 – 0.37	0.11
Speed of Sound	~2700 m/s	1500 m/s

Figure 11: Shear and Young's Moduli as a function of temperature. Tan delta is a measure of where the glass transition temperature is, and there is a 6 degree difference between the 2 samples



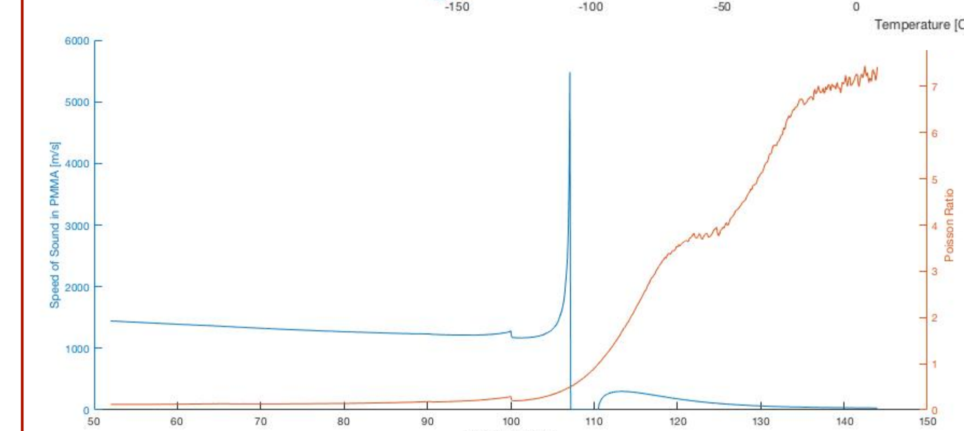


Figure 12: Calculated speed of sound and Poisson's Ratio as a function of temperature. The speed of sound becomes undefined around 108 degrees, illustrating a problem with the underlying rheometer and DMA data

Conclusions

The thermal penetration depth was successfully measured from both 4K video and ultrasound
- Because the speed of sound at high temperatures is unreliable, a full temperature characterization was not possible
- Ultrasound sensor was integrated into motor controls so future firings have an additional piece of data to work with
- Preliminary average speed of sound in TPD: 1.27 mm/us

Future Work:
- Fine tuning 4K video analysis
- Obtaining reliable speed of sound calculations
- Finding potential temperature curves within the TPD, optimized to fit a model across several hotfires

Bibliography

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Further Information

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