Aerospike Nozzle Design for a Hybrid Rocket

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What is a hybrid rocket?

A hybrid rocket uses a liquid oxidizer and a solid fuel. It combines,

- The mechanical simplicity of a solid rocket
- The high performance of a liquid rocket

The University of Toronto Aerospace Team (UTAT) builds N_2O-Paraffin hybrids.

Figure 1. UTAT Deliverance II Hybrid Rocket

What is an aerospike nozzle?

An aerospike is an altitude compensating nozzle which maintains a high efficiency over a wide range of altitudes as opposed to a traditional bell nozzle which is only efficient at a single altitude.

Design Challenges and Overview

- Few materials can withstand the operating temperatures that reach 3000 K
- Complex geometries and large operating pressures pose a mechanical challenge
- A lack of substantial prior art results in the absence of accurate models for predicting key flow transitions

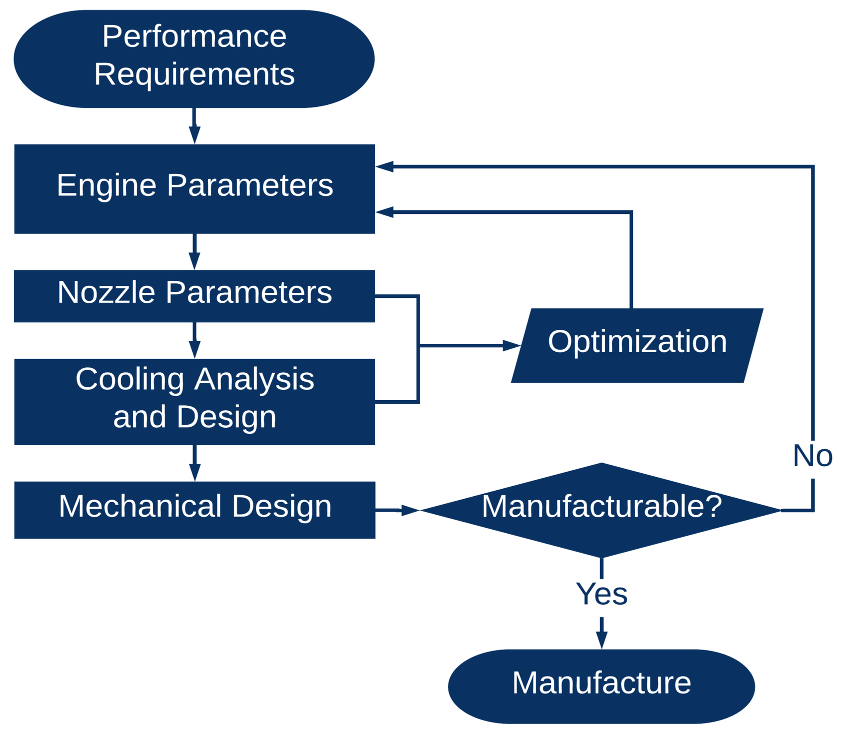

Figure 2. Aerospike nozzle design flowchart

Nozzle Contour

Assuming a Prandtl–Meyer expansion fan at the nozzle throat, the contour was designed through Angelino's method and truncated to 20% of the original length.

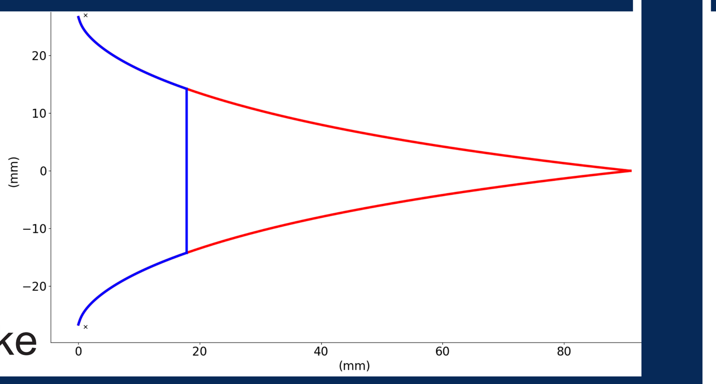

Figure 3. (Right) Full length and truncated aerospike

Nozzle Optimization

Computationally inexpensive methods for predicting plume properties and heat transfer (Mayer's and Method of Characteristics (MOC) respectively) were implemented for iterative optimization.

$$C(contour) = \alpha * thrust(contour) + \beta * heatduty(contour)$$

Equation 1. Optimization cost function

CFD Simulation

A compressible, viscous, turbulent simulation of the nozzle was run using a density-based CFD solver in OpenFOAM.

Key flow features expected were present,

- Open-wake formation
- Oblique shock
- Lip shock
- Shear layer

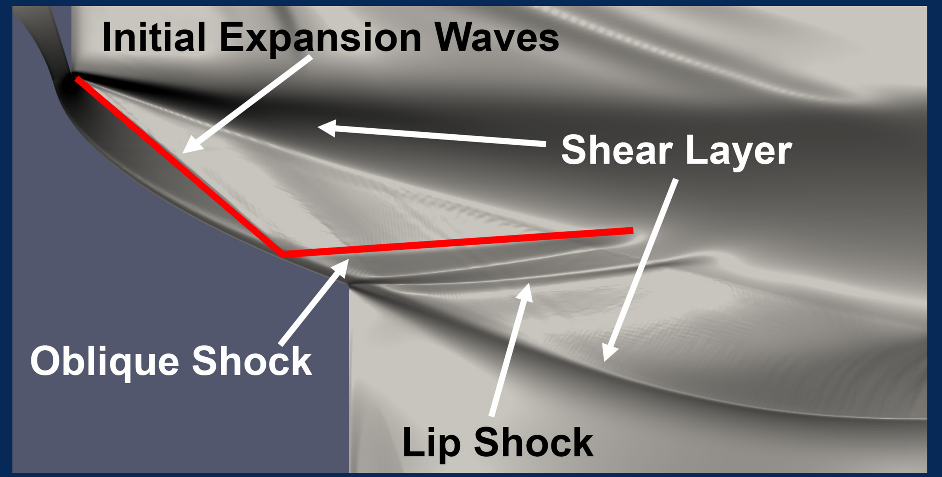

Figure 4. Numerical Schlieren diagram

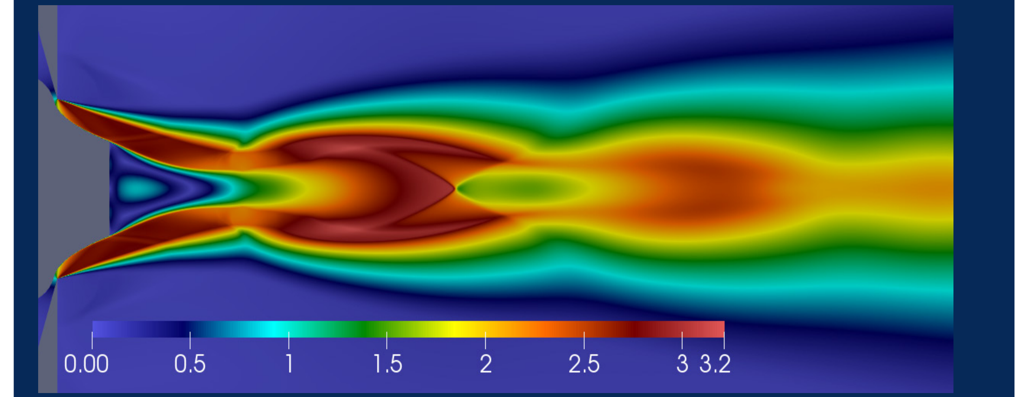

Figure 5. Mach contour at sea level

CFD vs MOC

High fidelity, low speed CFD results were used to validated the low fidelity, high speed Method of Characteristics (MOC) used for iterative optimization.

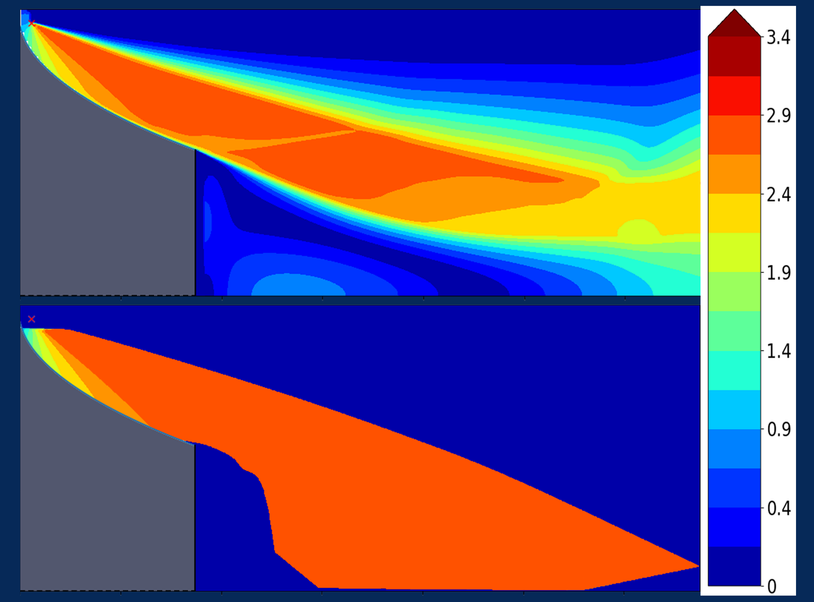

Figure 6. (Right) CFD and MOC Mach contour at sea level

Aerospike vs Bell Nozzle

Implementing an aerospike in the UTAT rocket 'Defiance' would result in a 7.2% increase in apogee from 14.4 km to 15.6 km.

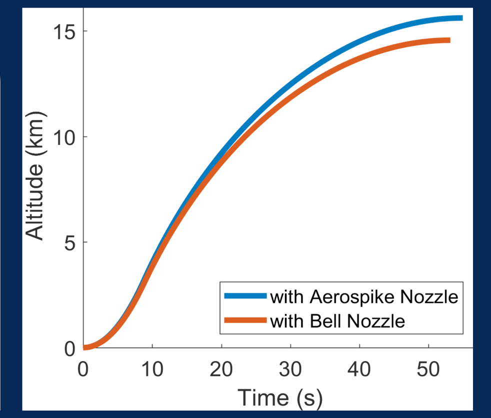

Figure 7. (Right) Defiance flight profile for differing nozzles

Cooling System

N_2O can serve as a coolant due to its high vapour pressure at room temperature (4.8 MPa) and available heat of vaporization

Active cooling

- Copper nozzle due to high heat conduction
- Coolant flowrate sized to keep nozzle below 700 K
- Feasible if planned total firing time > 40s

No cooling

- Graphite erosion rate: 0.03 – 0.05 mm/s
- Re-usable 3 to 5 times at 4 second burns

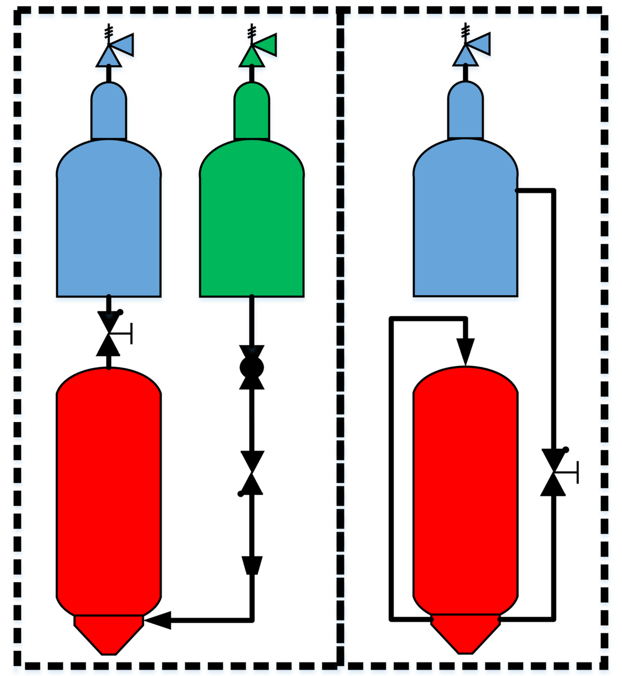

Figure 8. Dump (left) and Regenerative cooling (right) setup with oxidizer, coolant, combustion chamber and nozzle

Mechanical Design

- A copper nozzle with 6mm cooling channels, and a graphite nozzle with no channels were designed.
- A N_2O-Paraffin lab scale hybrid engine was designed to test the nozzle.

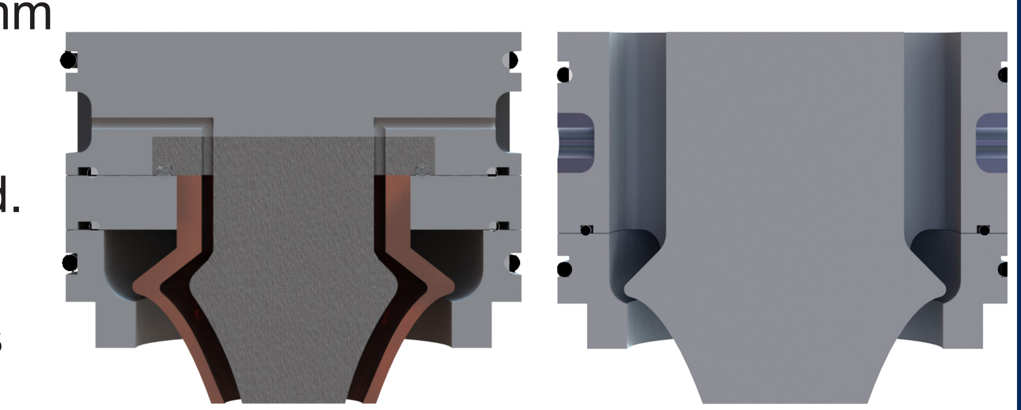

Figure 9. Copper (left) and Graphite (right) nozzles

Figure 10. N_2O-Paraffin lab scale engine

Environmental Analysis

- N_2O, with a GHG equivalent 265 times higher than CO_2 results in the bulk of GHG emissions when used for dump cooling.
- An optimal firing time will produce steady state test data while reducing GHG emissions.

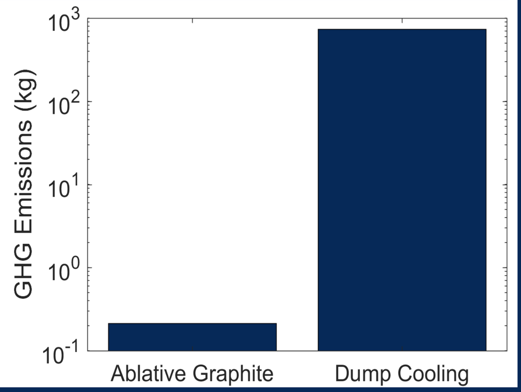

Figure 11. (Right) GHG emissions for differing nozzles

Future Work

Manufacturing of nozzle and engine components is ongoing and testing will occur within the next few months.

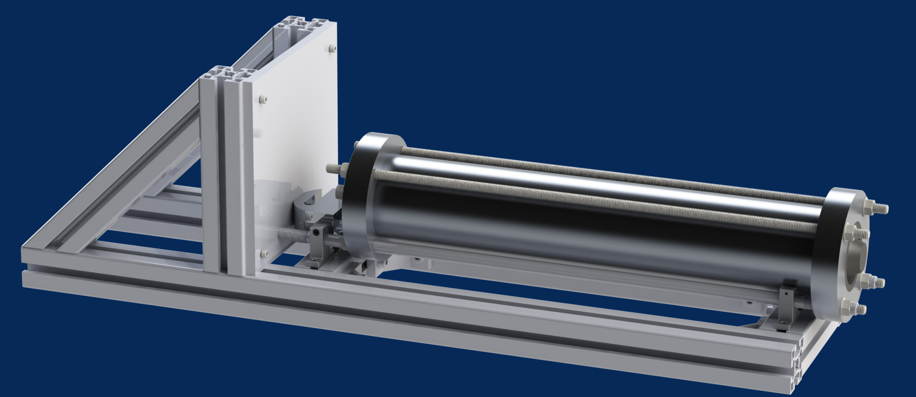

Figure 12. Engine mounted on test