AEROSPIKE ENGINE DESIGN THROUGH OPTIMIZATION TECHNIQUES

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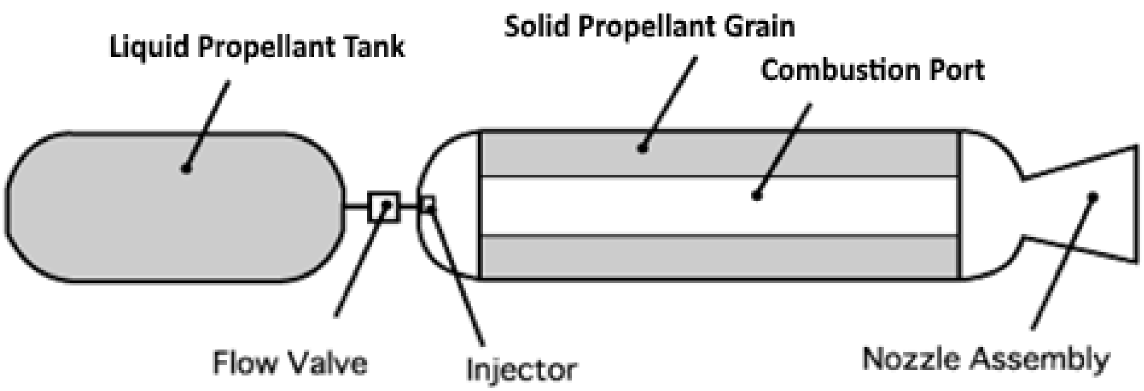
CASI ASTRO 2018

University of Toronto Aerospace Team Rocketry Division

- Specializes in the design and manufacture of hybrid sounding rockets

- Nitrous Oxide: available, self-pressurizing, storable
- Paraffin Wax: High regression rate = high thrust

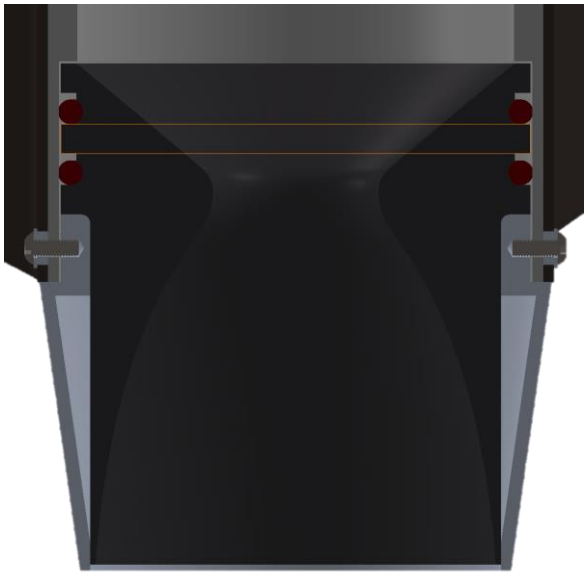


Defiance: The Canadian Record Breaker

Goal: Achieve >15 km altitude

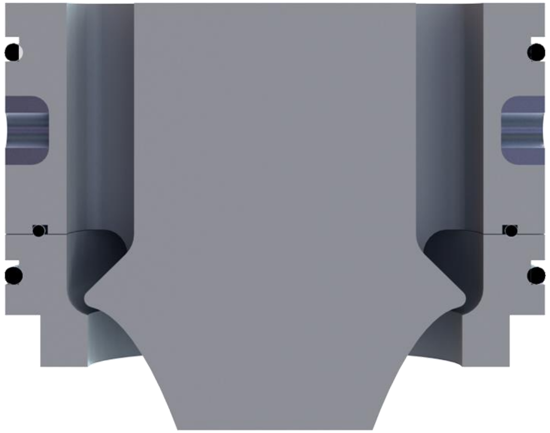
Defiance (above) and Deliverance II

Maximizing Nozzle Performance



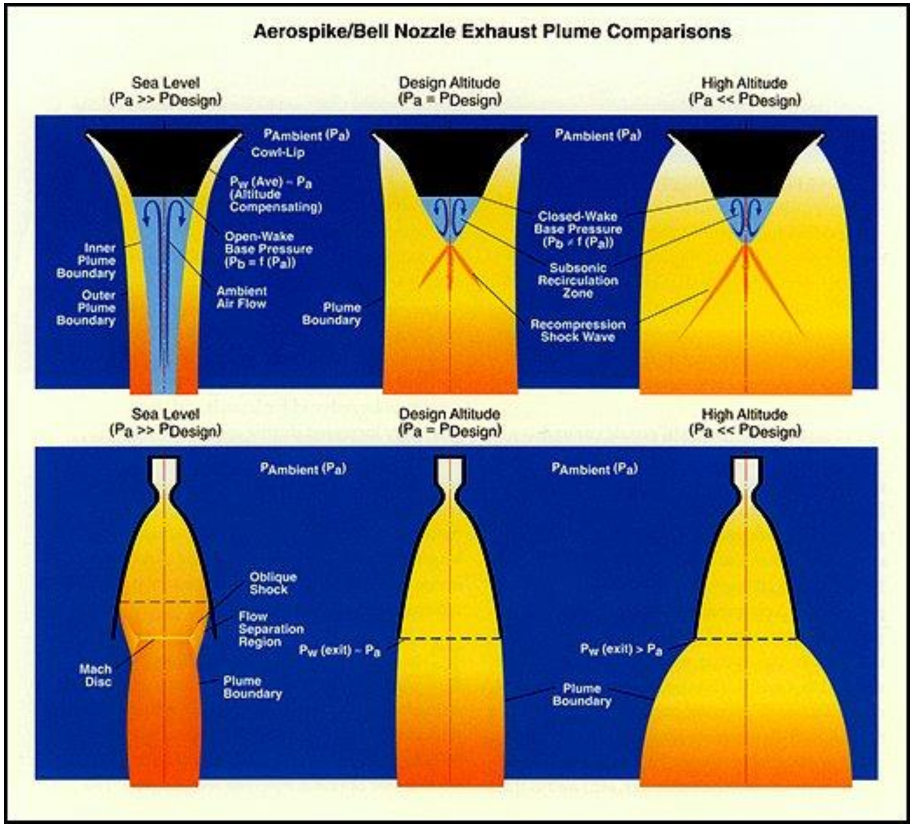
TIC nozzle

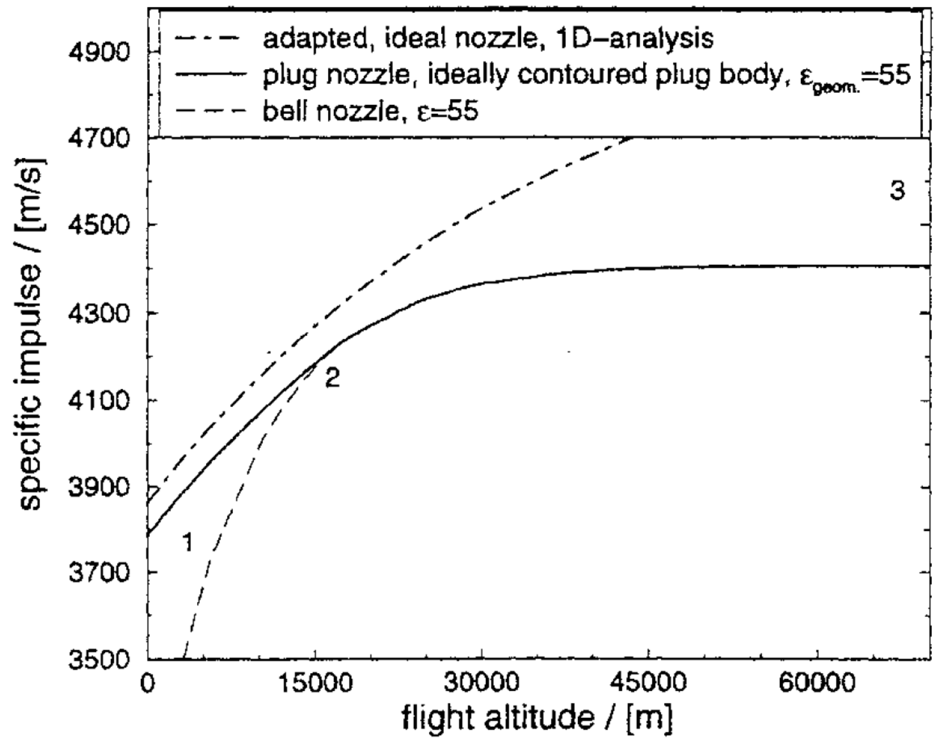
Composite Nozzle



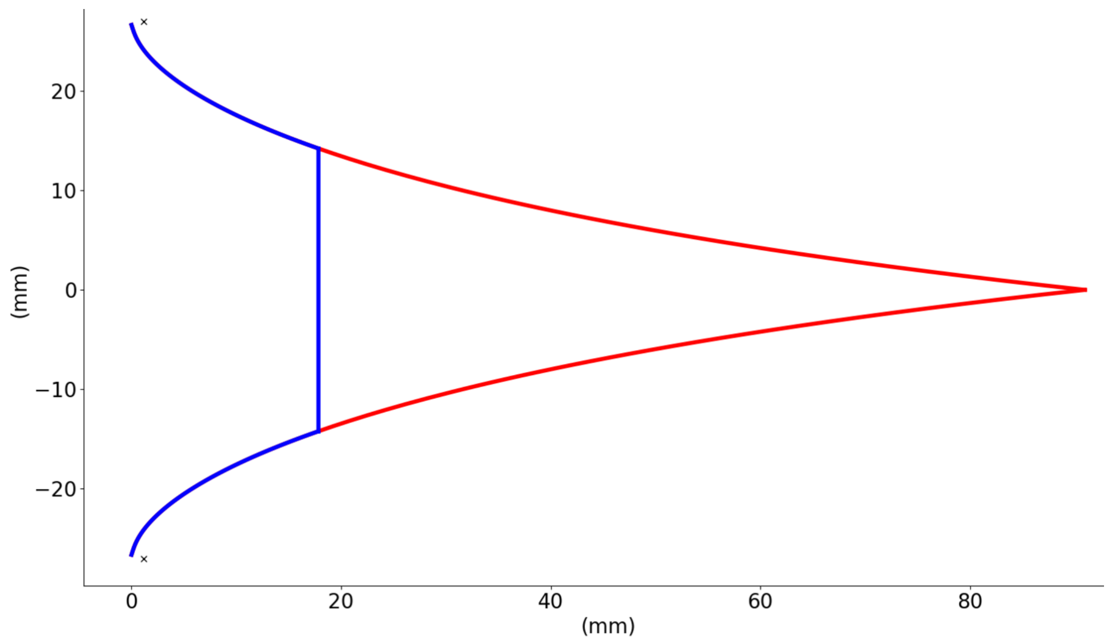
Aerospike Nozzle

AEROSPIKE NOZZLE



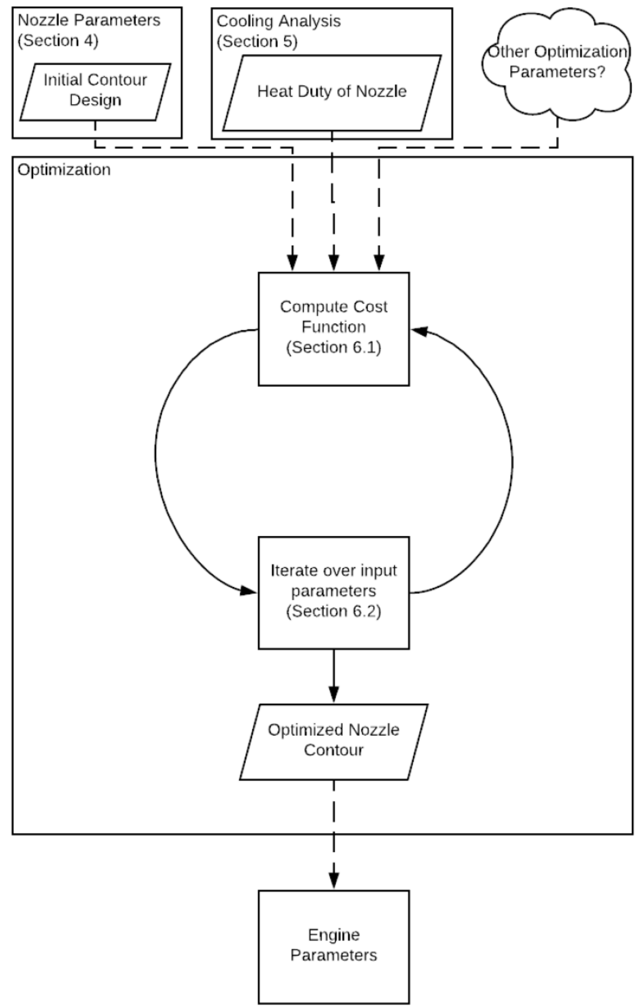


NAÏVE DESIGN



- 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.

OPTIMIZATION FRAMEWORK



OPTIMIZATION METHOD #1

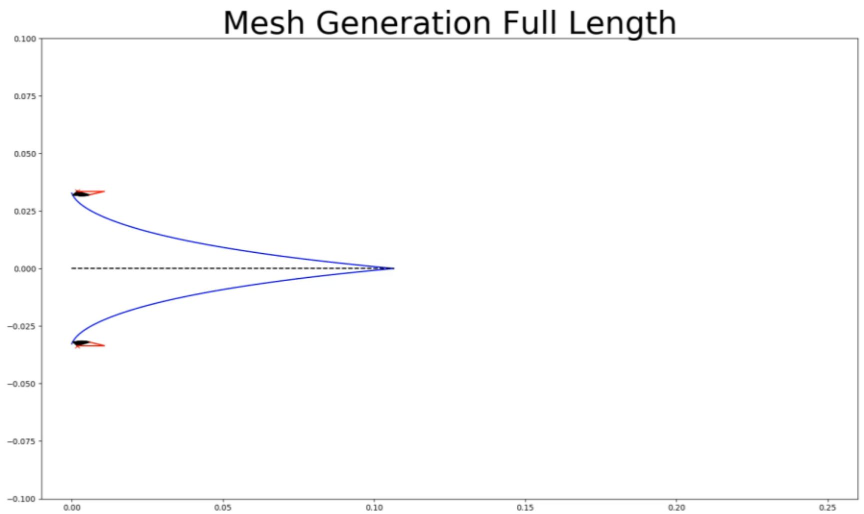
- Weighted sum of the thrust and heat duty paramaterized by the design altitude and truncation

$$C(alt_d, tr) = \alpha * thrust(alt_d, tr) + \beta * heatduty(alt_d, tr)$$

- alt_d = design altitude
- tr = truncation amount

COST FUNCTION EVALUATION – THRUST

- Computational Fluid Dynamics is natural choice for evaluation
  - However, very expensive
- Method of Characteristics
  - Using three-dimensional irrotational equations of flow
  - Can require less points for the same level of accuracy compared to finite difference based CFD [3]



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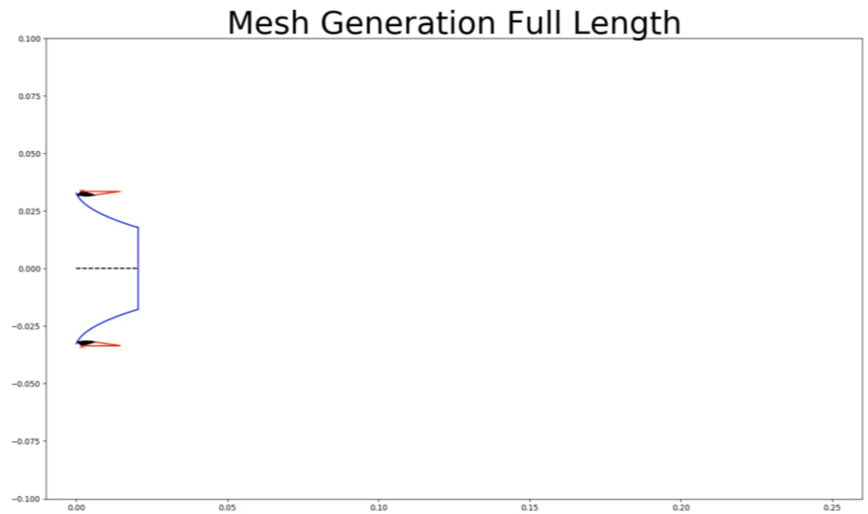

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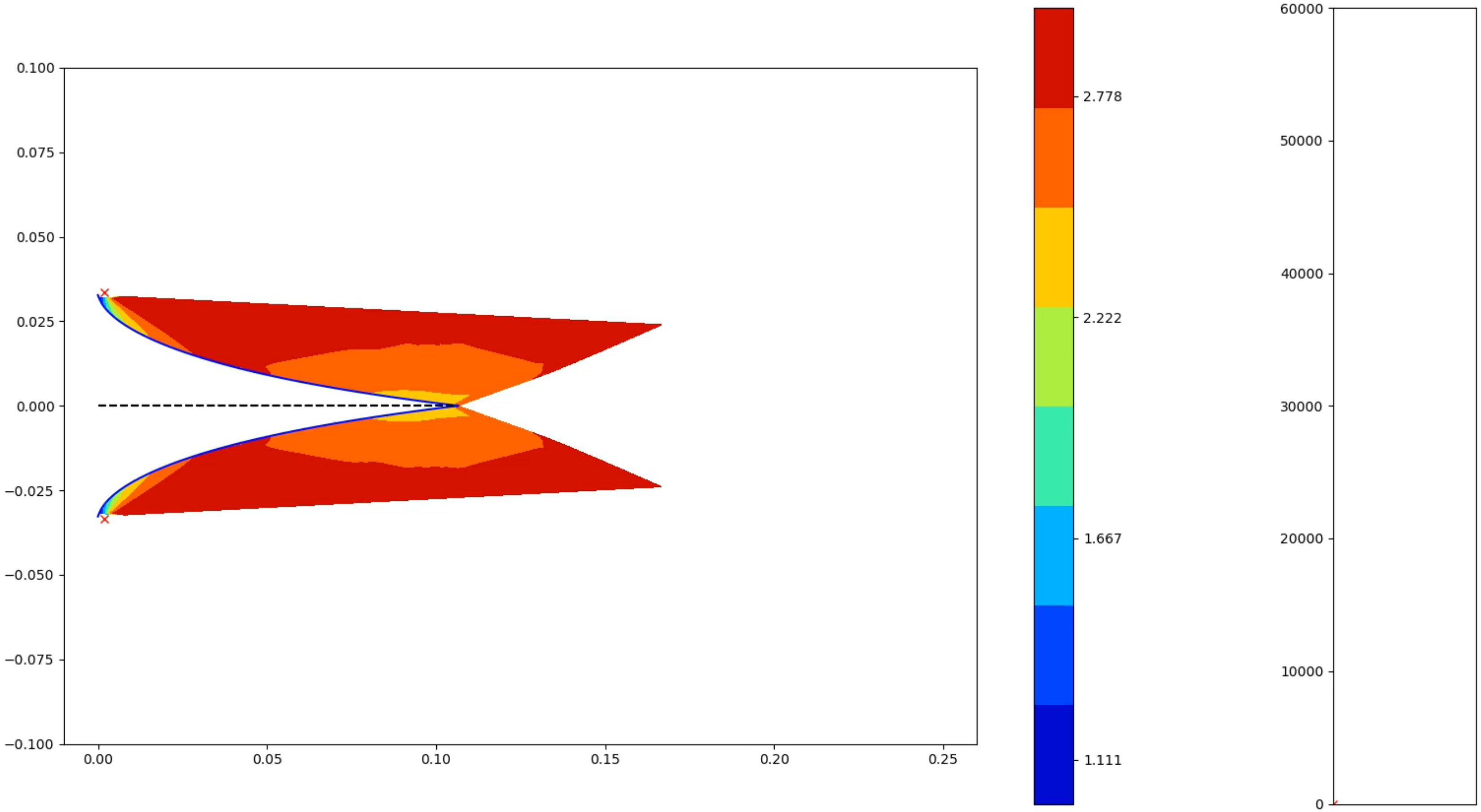

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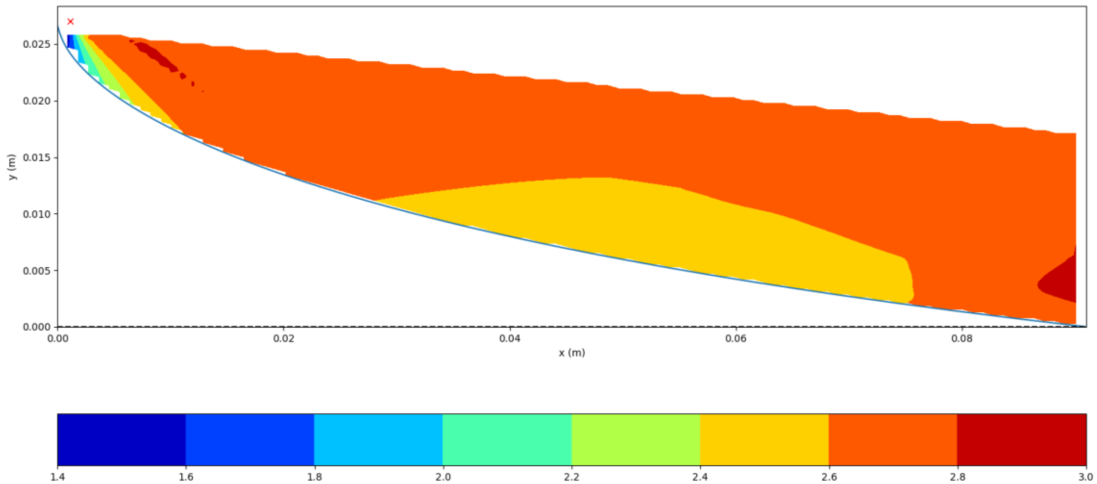
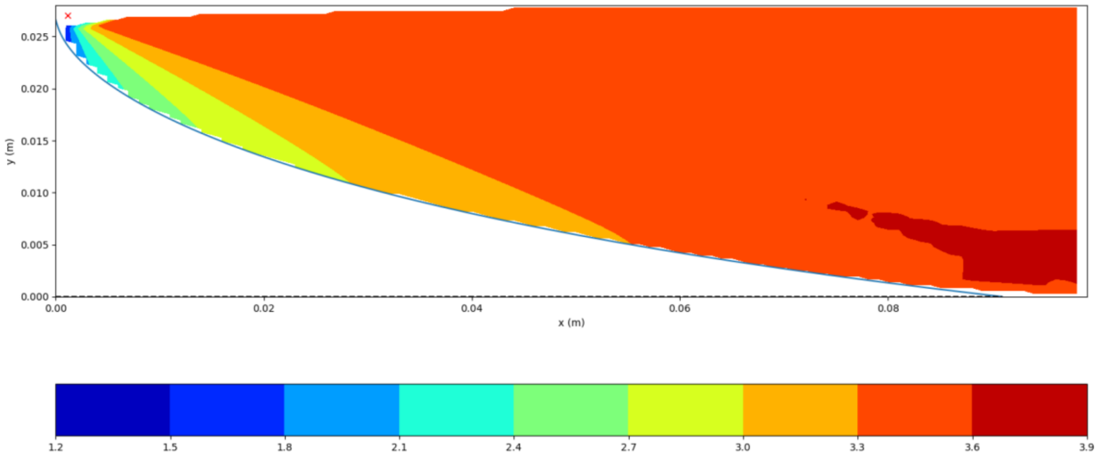
MOC EVALUATION



- Sea Level
- Note Under-expansion

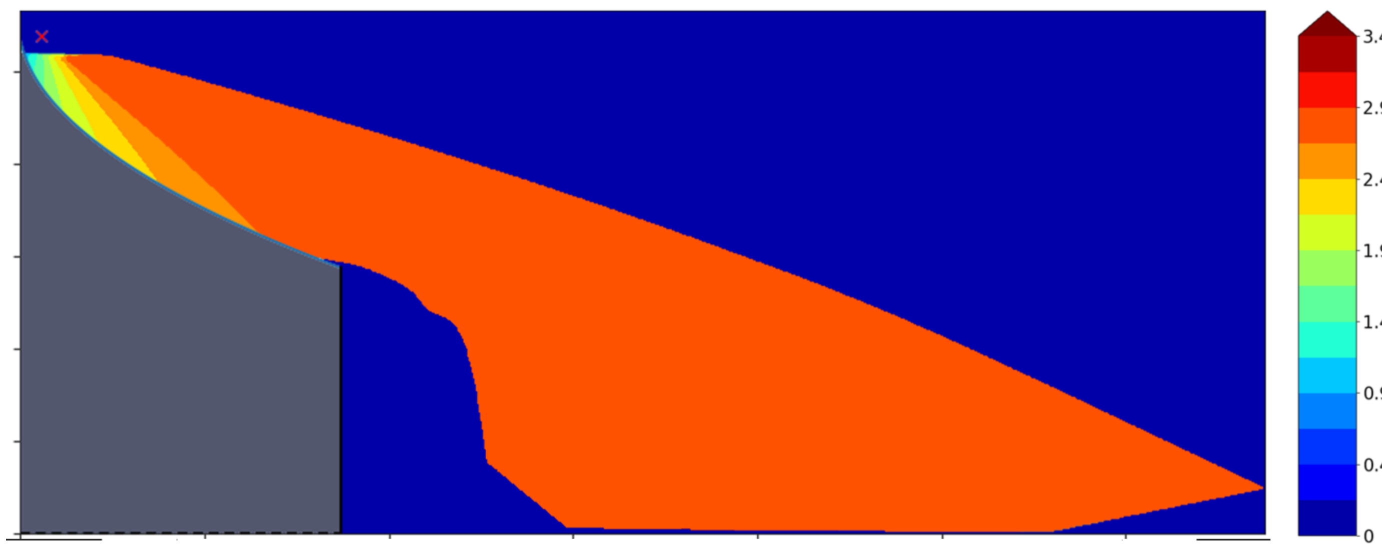


- Design Altitude

TRUNCATED AEROSPIKE EVALUATION

- Need to predict pressure at the base of the truncated nozzle
- Empirical model by the University of Rome

$$p_b = p_{atm}\left(0.05 + \frac{0.967}{1 + \frac{\gamma - 1}{2} M_{atm}^2}\right)^{\Phi} \qquad \Phi = \frac{-0.2\phi^4 - 5.89\phi^2 + 20179.84}{\phi^4 + 20179.84}$$

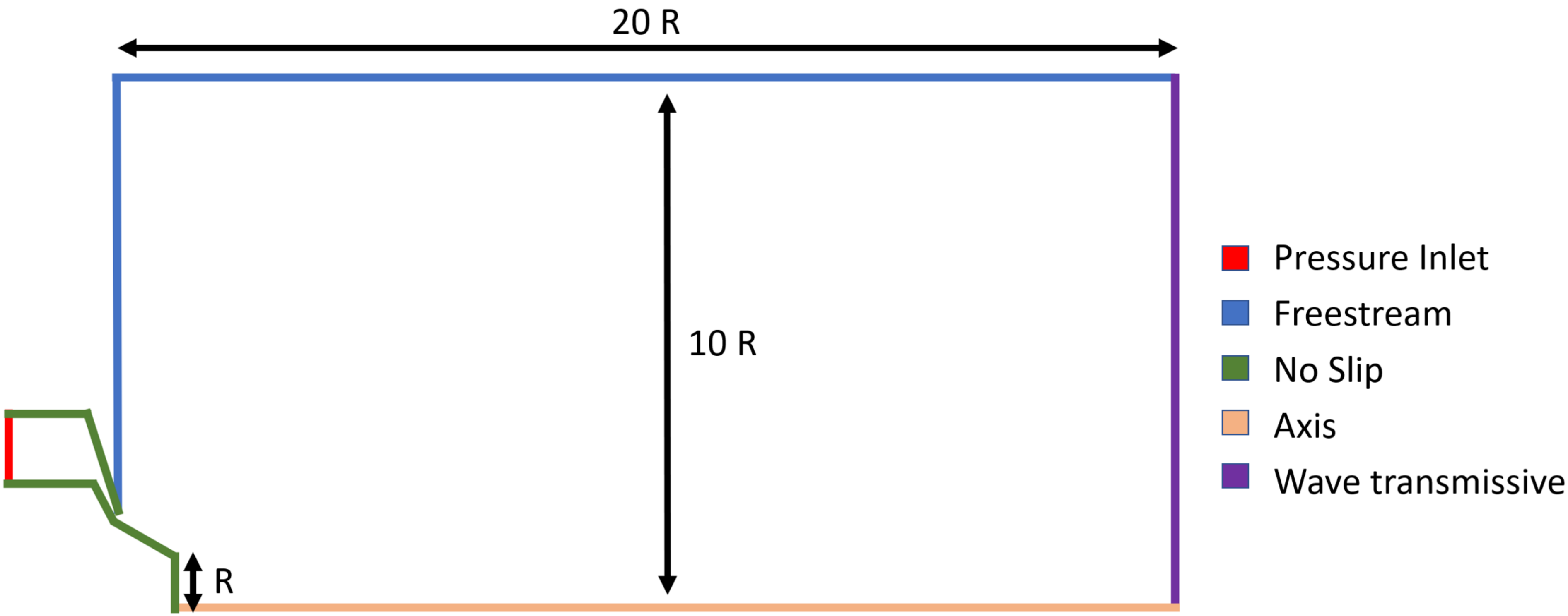


COMPUTATIONAL FLUID DYNAMICS

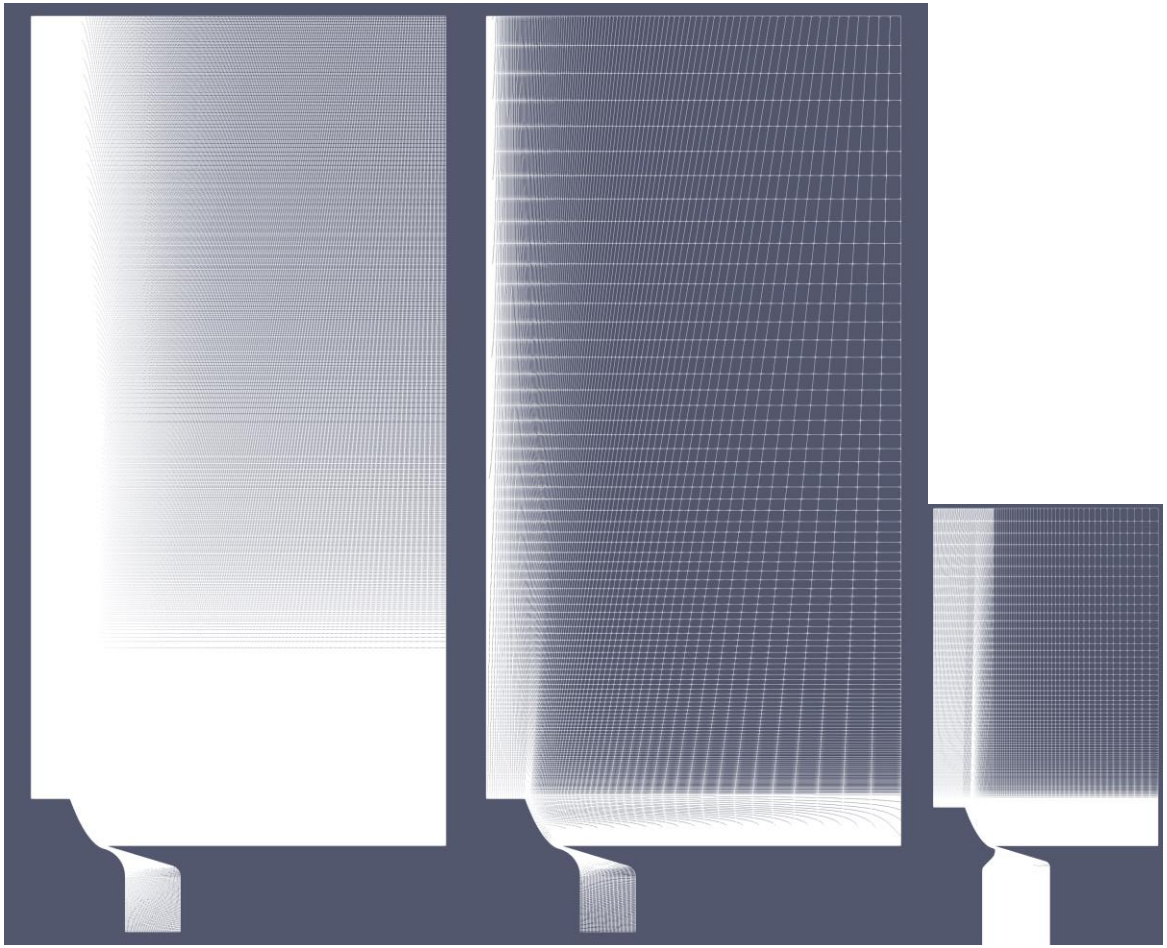
- **rhoCentralFoam:** OpenFOAM Density-based compressible flow solver
  - Based on central-upwind schemes of Kurganov and Tadmor
- **Turbulence Model:** $k - \omega\ SST$
- **Time Step:** $1e^{-10}$ s (Co = 0.5)
- **Total Time:** 10 ms

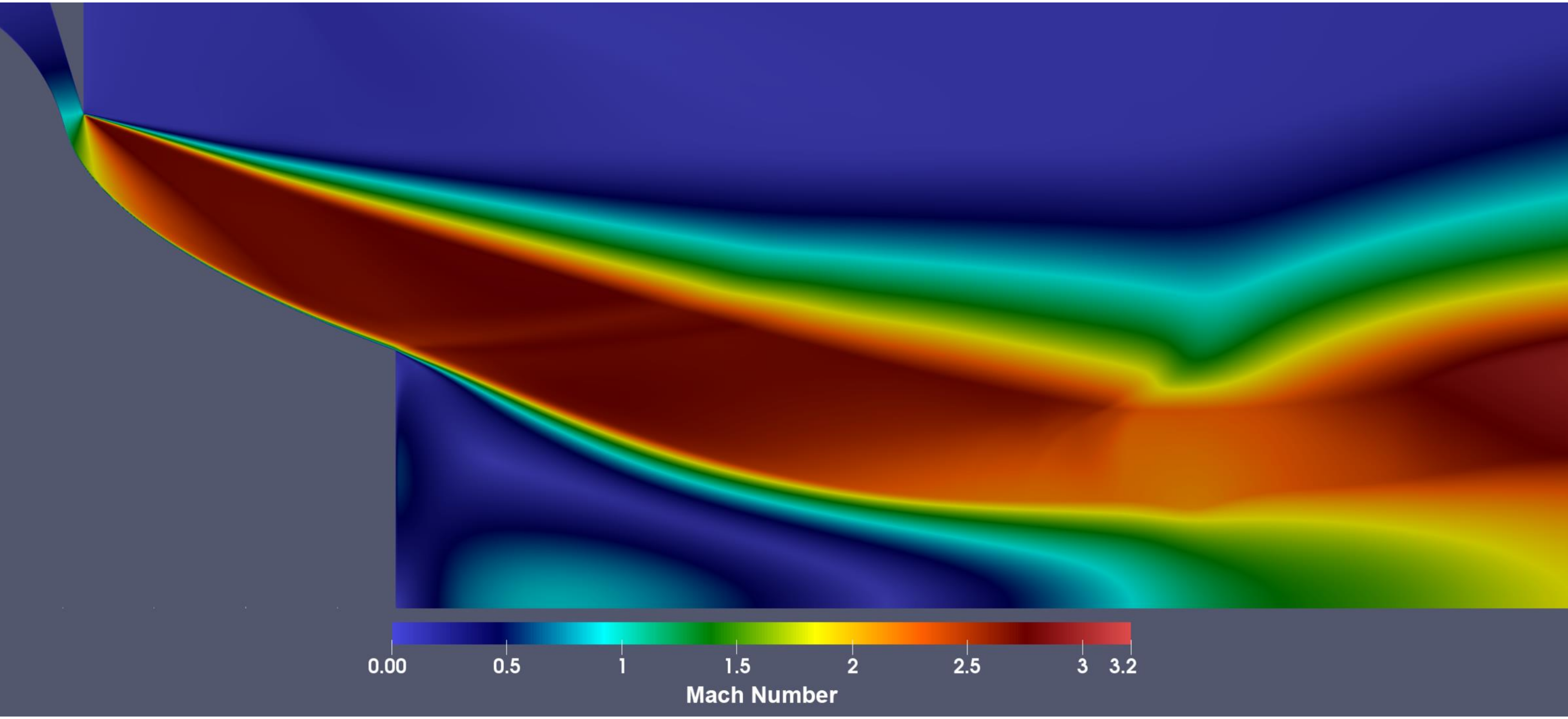
- **Gas Properties:**
  - **Equation of state:** Ideal Gas Law
  - **Transport Model:** Sutherland
  - **Thermodynamic Model:** Constant C_p = 2015 J/Kg K
  - **Molecular weight:** 23.1 g/mol
- Parallel cloud computing on Amazon AWS servers

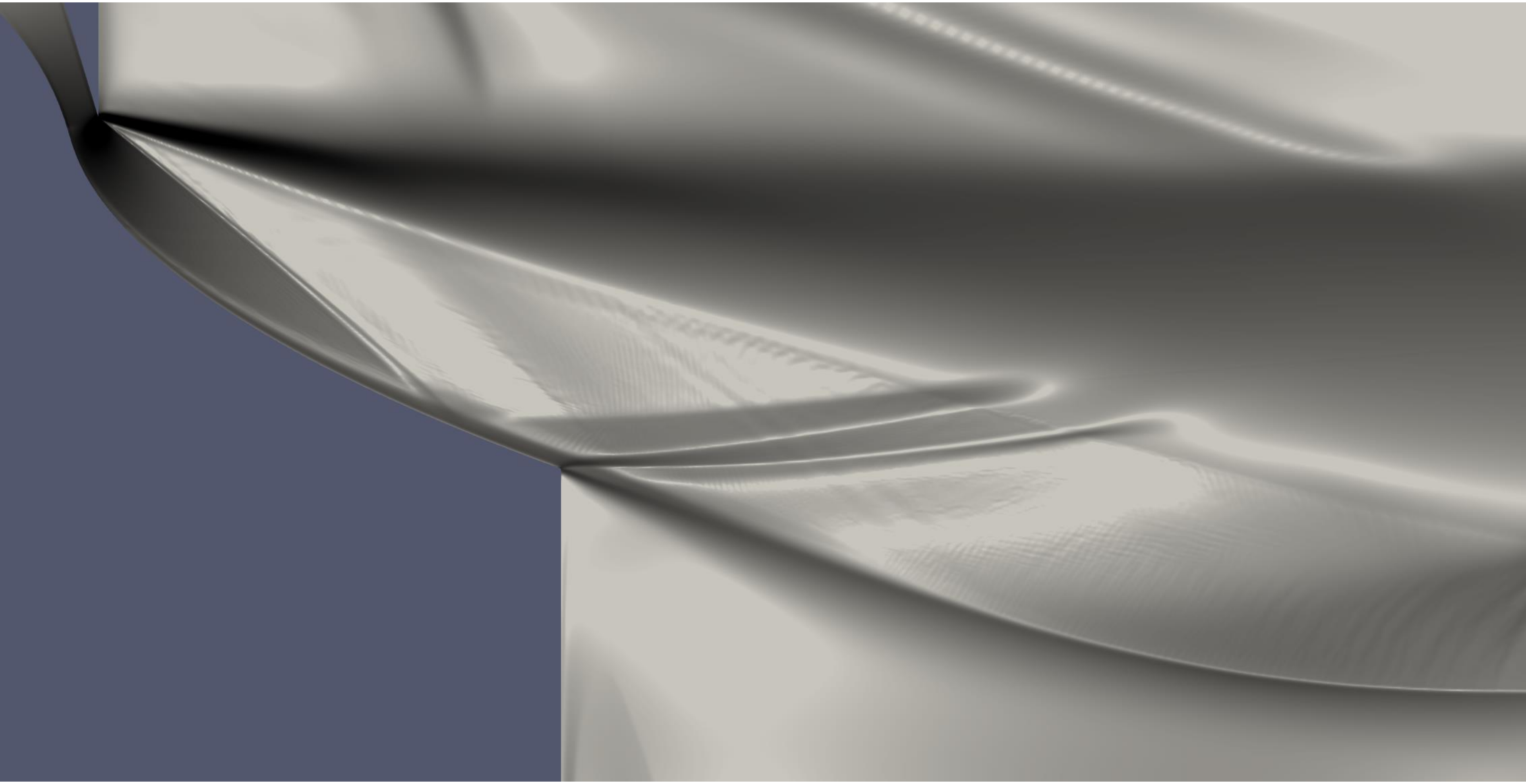
BOUNDARY CONDITIONS

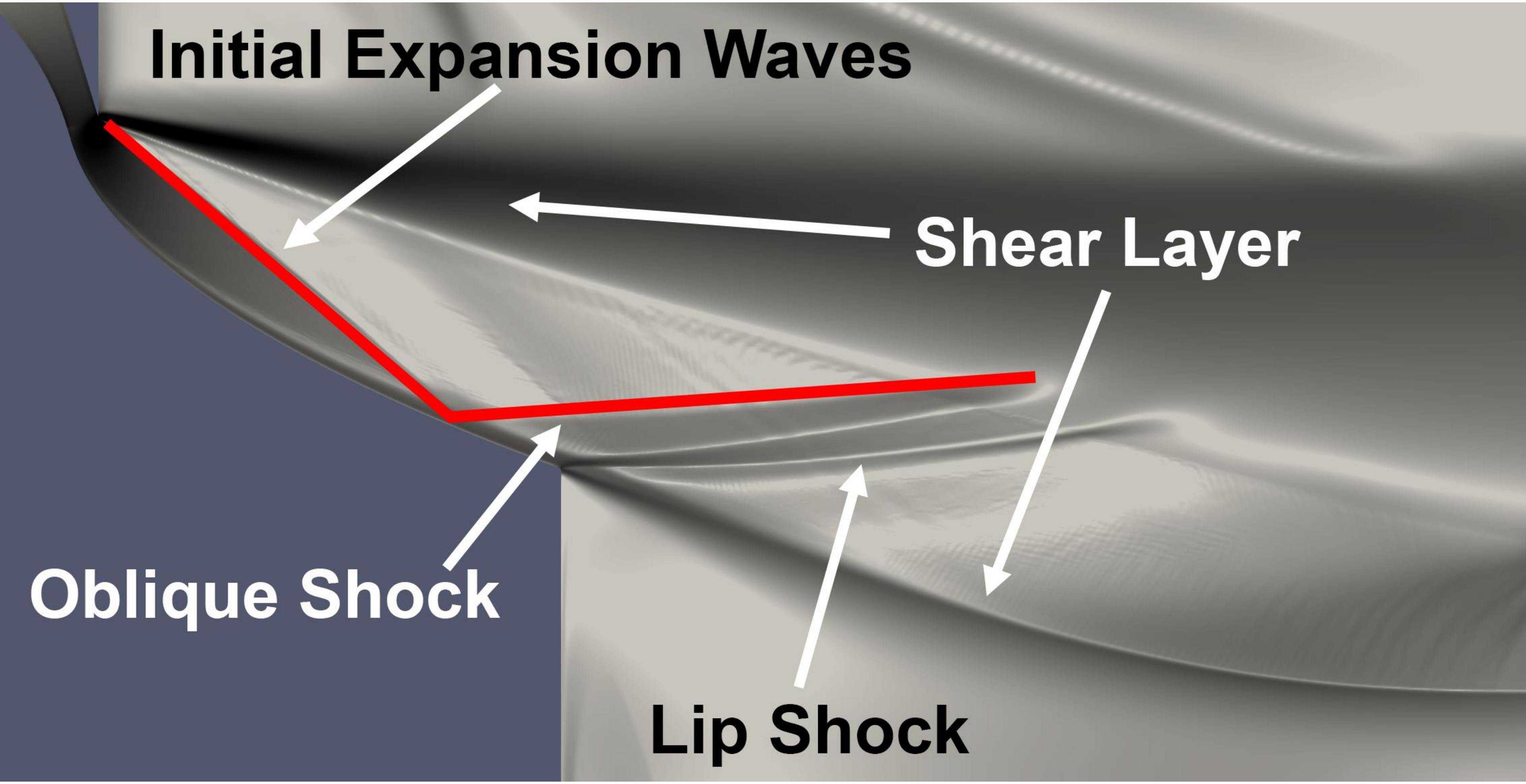


MESH INDEPENDENT SOLUTION

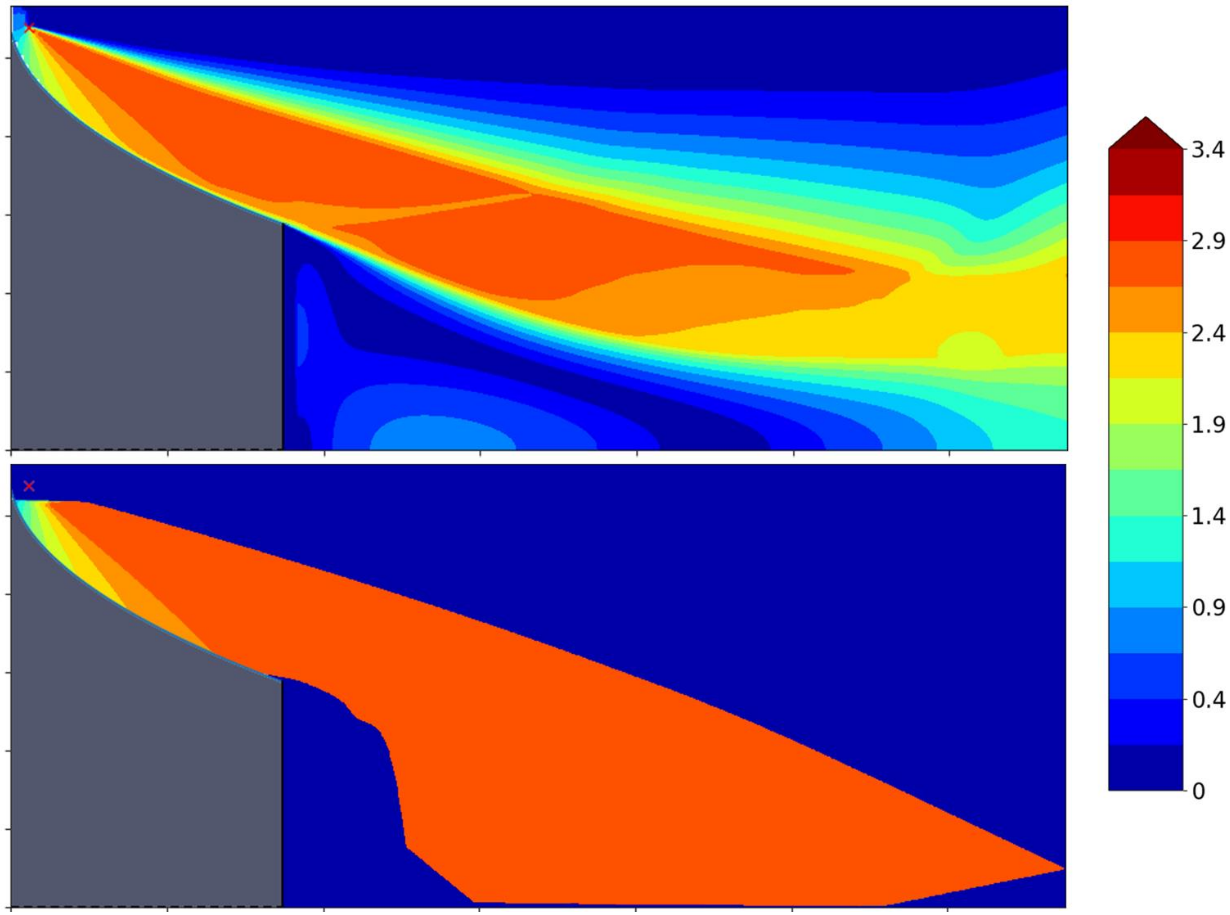



0.00
0.5
1
1.5
2
2.5
3
3.2
Mach Number

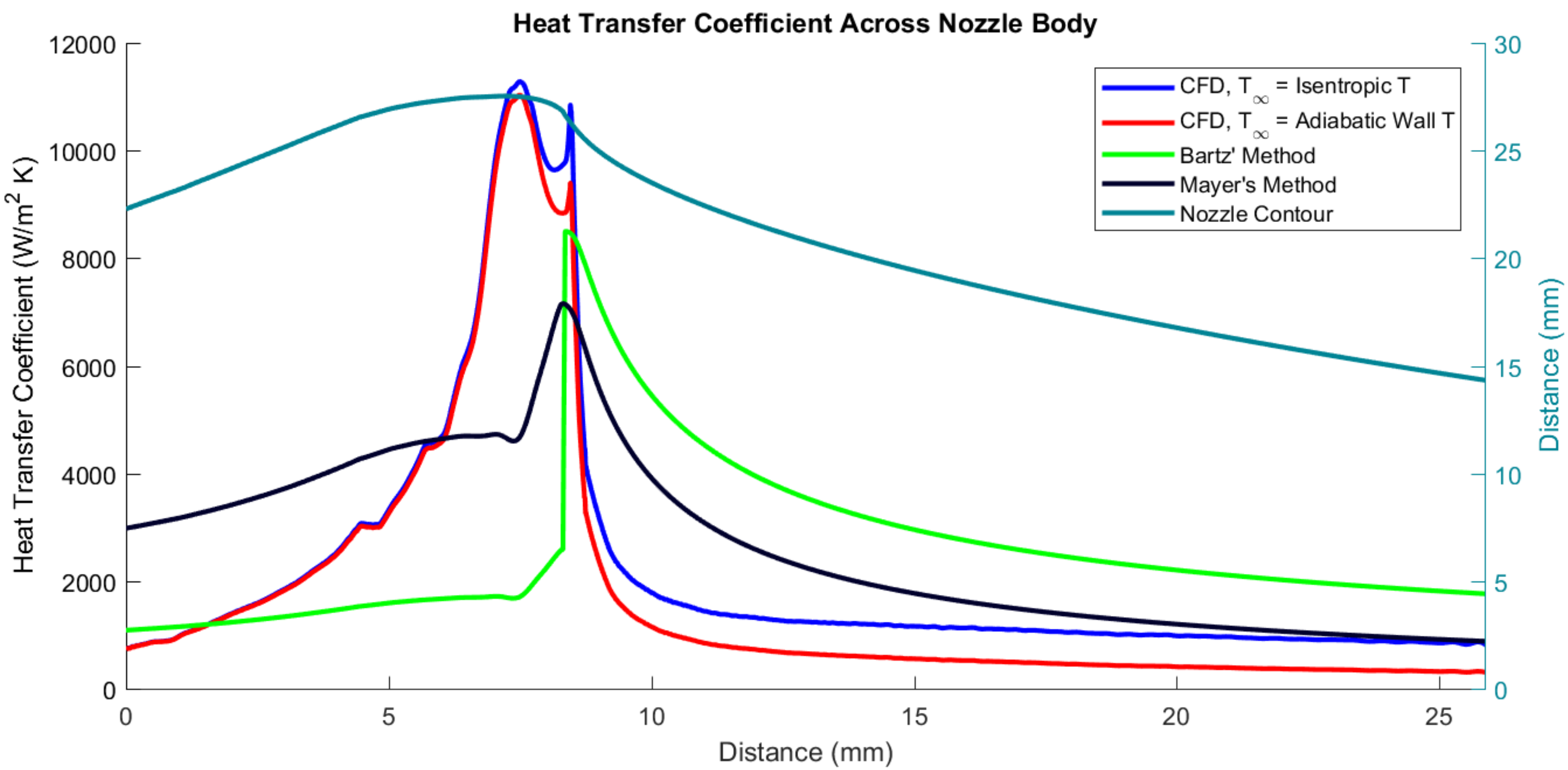



Initial Expansion Waves
Shear Layer
Oblique Shock
Lip Shock

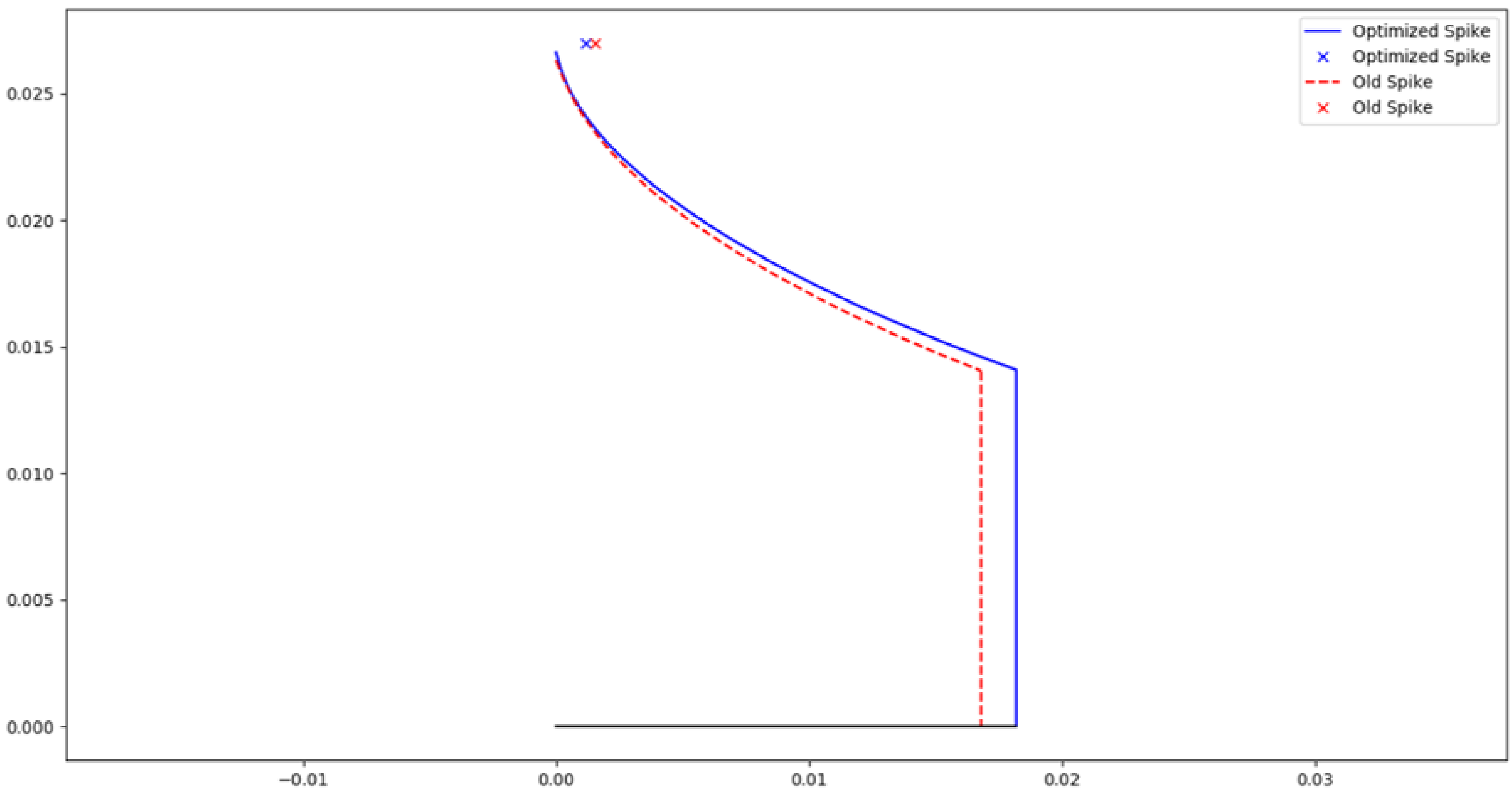
MOC VERIFICATION



COST FUNCTION EVALUATION – HEAT LOAD



OPTIMIZATION RESULTS



OPTIMIZATION METHOD #2

- Cost function is also weighted sum of the thrust and heat duty
  - This time parameterized by the finite contour points

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

- Contour is given by the spline interpolation of points

$$(x_0, r_0, x_1, r_1, ..., x_n, r_n)$$

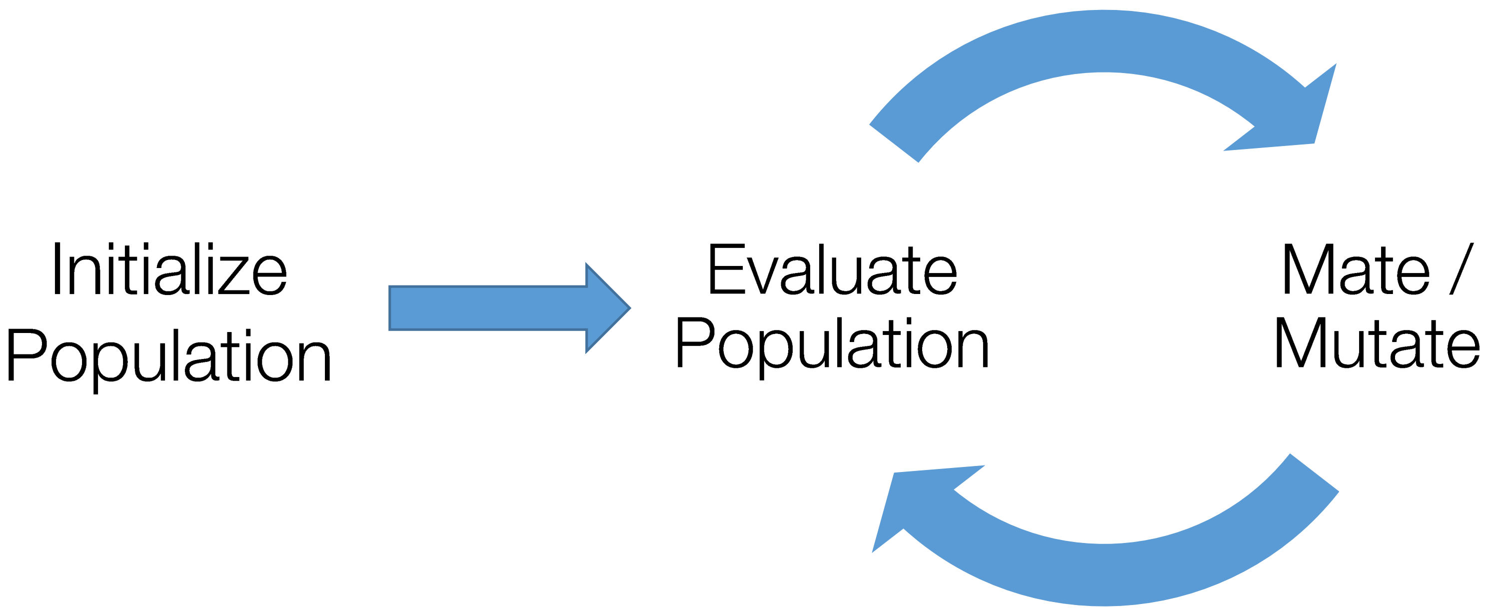
- Where,

$$(x_0 < x_1 < ... < x_n)$$

OPTIMIZATION ALGORITHMS

Gradient Methods	• Challenging to evaluate with an expensive cost function, making progress extremely slow • Prone to getting caught in local minimum
Response Surface Methods	• Reasonable choice for exploring design space • Requires significant evaluation of cost function • Shown to perform worse than GA's when cost is difficult to evaluate [1]
Genetic Algorithms	• Require one evaluation of cost function per population member • Good at exploring the design space without getting trapped in local min.

GENETIC ALGORITHM OVERVIEW



INITIALIZE POPULATION

- Use Angelino's method to define an ideal nozzle contour
- Simultaneously solve:

$$\frac{l}{l_t} = \epsilon M(M)$$

$$\alpha = \mu(M) - \nu(M)$$

- Where *l* is the characteristic line length at different points on the nozzle contour
- Provides a nozzle contour under the assumption of *quasi-1D, isentropic, steady supersonic flow*
- Add random noise to generate different contours of population (300 used in our work)

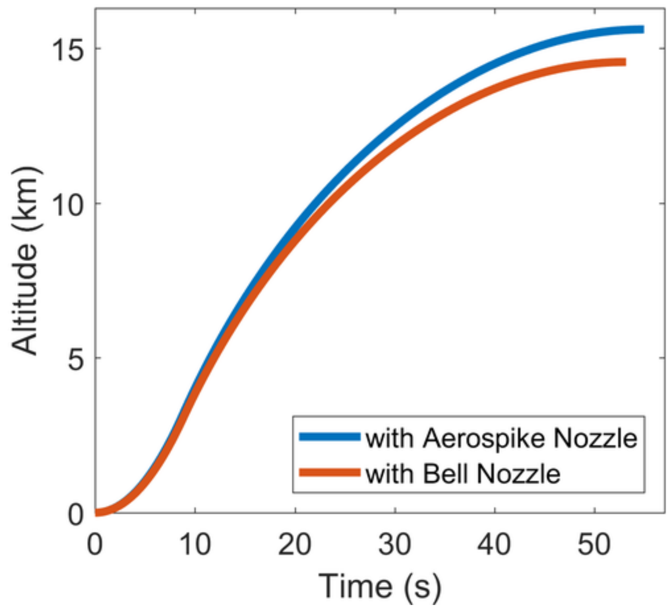
MUTATE AND MATE POPULATION

- Using Distributed Evolutionary Algorithms in Python (DEAP)
  - A two point crossover with a probability of 0.5 was chosen
  - Gaussian mutation with a mutation probability of 0.2
- Next generation is created through mutation and mating of previous members of population

ISSUES PRESENT

- Rapidly created contours that brought evaluation methods past their limits.
- Rapid convergence to highly performing contours shows the potential of GA in aerospike nozzle contour optimization
- Patching weaknesses in the method of characteristics – namely mesh fold back – would create an optimized contour that takes into account lesser assumptions made with evaluation methods

AEROSPIKE VS BELL NOZZLE



Bottom line: 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.

Conclusion

- A framework for Aerospike nozzle optimization was introduced
- Two cost functions were evaluated utilizing gradient based approaches and genetic algorithms
- Showed that optimization of an Aerospike engine over a set of design parameters is possible

REFERENCES

[1] Amiri M., A.A. Najfi, K. Gheshlaghi, *Response Surface Methodology and Genetic Algorithms*, Journal of Applied Science, vol. 8, pp. 2732-2738

[2] Angelino Gianfranco, *Approximate Method for Plug Nozzle Design,* AIAA Journal, pp. 1834-1835, vol. 2, 1964

[3] Anderson, *Modern Compressible Flow with Historical Perspective,* 3rd Edition, McGraw Hill Education

QUESTIONS?

Emerson Vargas Niño
Rocket Propulsion Lead