CFD EVALUATION OF NUMERICALLY EFFICIENT MODELS FOR HEAT TRANSFER AND THRUST ESTIMATION IN AEROSPIKE ENGINE DESIGN

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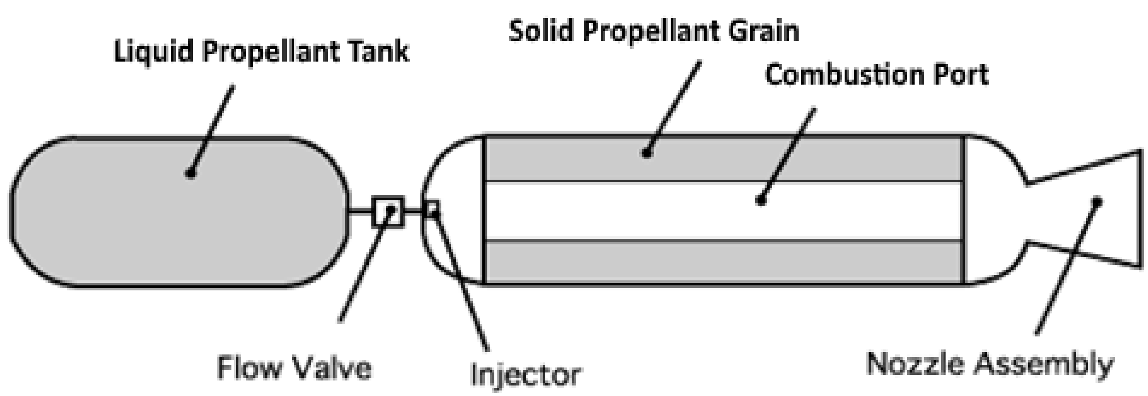
CASI ASTRO 2018

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

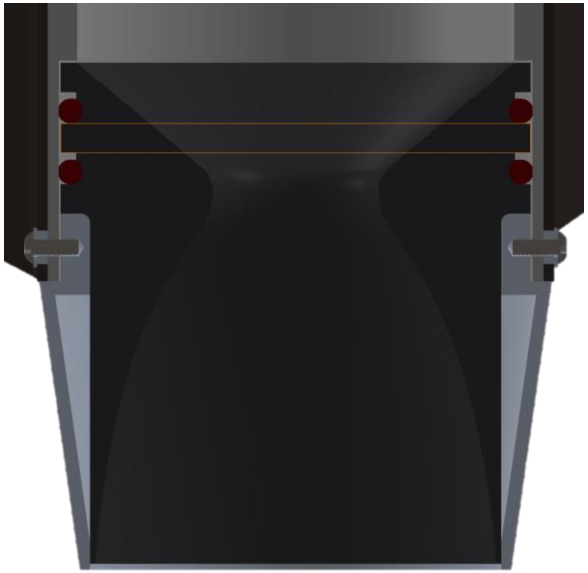


Defiance: The Canadian Record Breaker

Goal: Achieve >15 km altitude

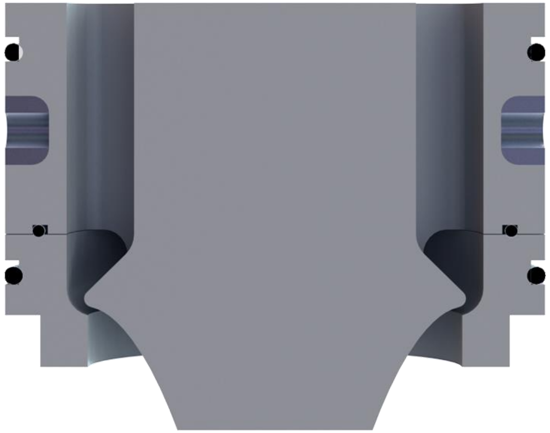
Defiance (above) and Deliverance II

Maximizing Nozzle Performance



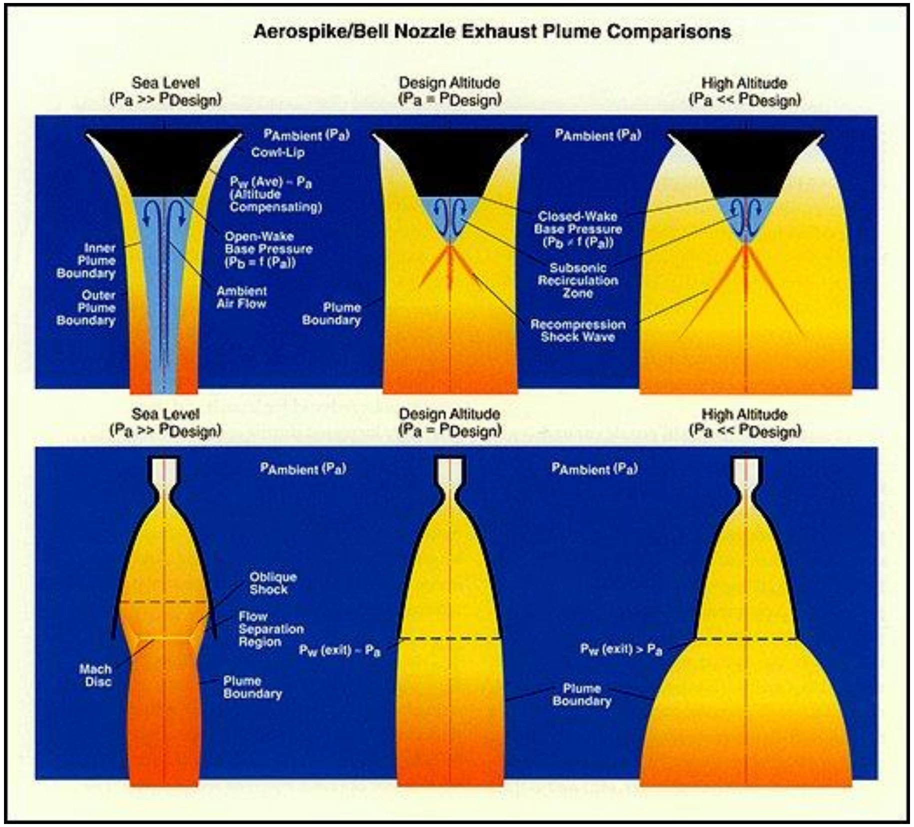
TIC nozzle

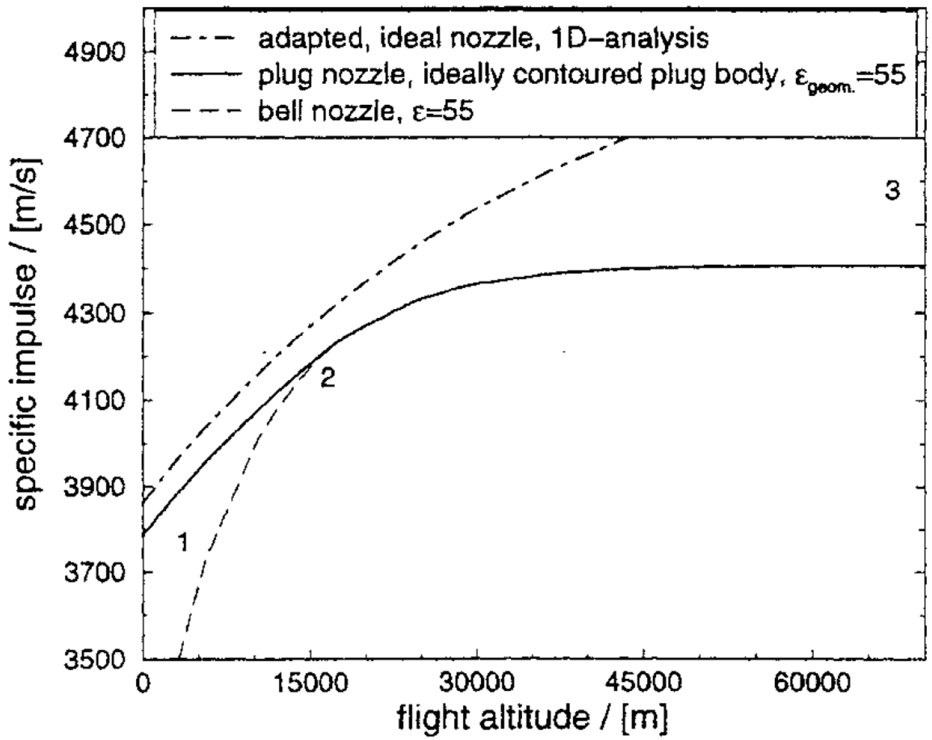
Composite Nozzle



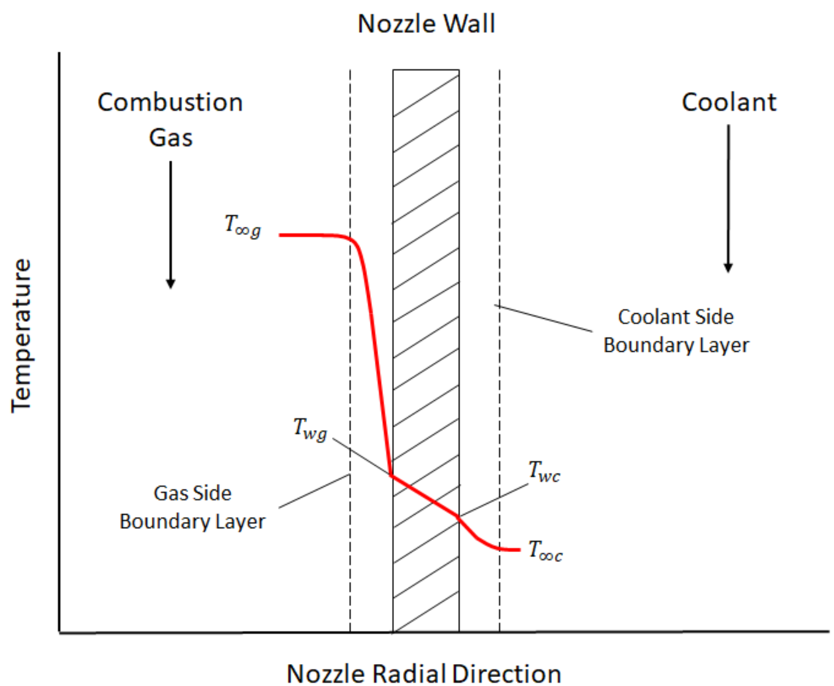
Aerospike Nozzle

AEROSPIKE NOZZLE





Heat Transfer Estimation



Combustion side:

- Convection dominant
- Surface Temperature at 700 K

$$q_{conv} = h_g\left(T_{\infty g} - T_{wg}\right)$$

Heat transfer coefficient:

- Bartz' Method (1957)
- Mayer's method (1961)
- Computational Fluid Dynamics (CFD)

Coolant side:

- Pre-dry out boiling regime
- Two-phase boiling heat transfer coefficient
  - Shah's correlation (1980)
  - With modified Boiling number developed by Lemieux, Pastrone, & Sanchez (2015)

Bartz' Method

- Based on traditional correlation used for turbulent flow in pipes
- Widely used for bell nozzles

Overview

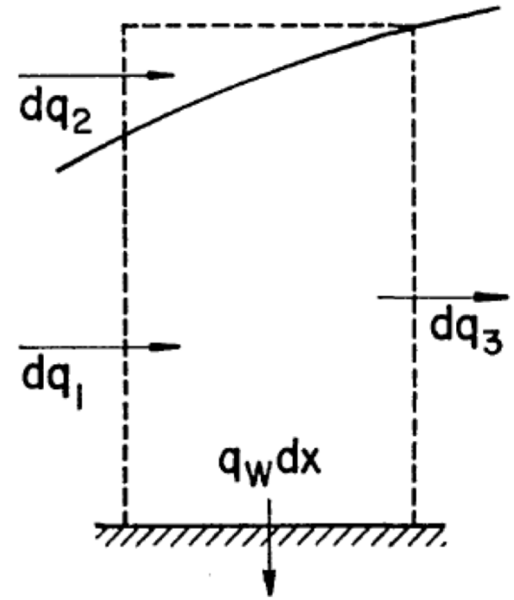
- Fully-developed flow
- Steady State

$$Nu = C(Re)^{0.8}(Pr)^{0.4}$$

$$h_g = \left[\frac{0.026}{D_t^{0.2}}\left(\frac{\mu^{0.2}C_p}{Pr^{0.6}}\right)_0\left(\frac{p_c}{C^*}\right)^{0.8}\left(\frac{D_t}{r_c}\right)^{0.1}\right]\left(\frac{A_t}{A}\right)^{0.9}\sigma$$

$$\sigma = \left[\left(\frac{1}{2}\frac{T_{wg}}{T_0}\left(1+\frac{\gamma-1}{2}M^2\right)+\frac{1}{2}\right)^{0.8-\left(\frac{w}{5}\right)}\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{w}{5}}\right]^{-1}$$

Mayer's method



- Developed for external expansion nozzles
- Much less common
- More difficult to apply

Overview

- Boundary layer balance
- Steady State

$$h_2(s) = \frac{0.0296\beta^{5/4}\overline{Pr}^{-2/3}\rho_\infty \bar{C}_{p,\infty} U_\infty}{\left(\int_0^s \beta^{\frac{5}{4}} \rho_\infty U_\infty \mu_\infty^{-1} ds\right)^{1/5}}$$

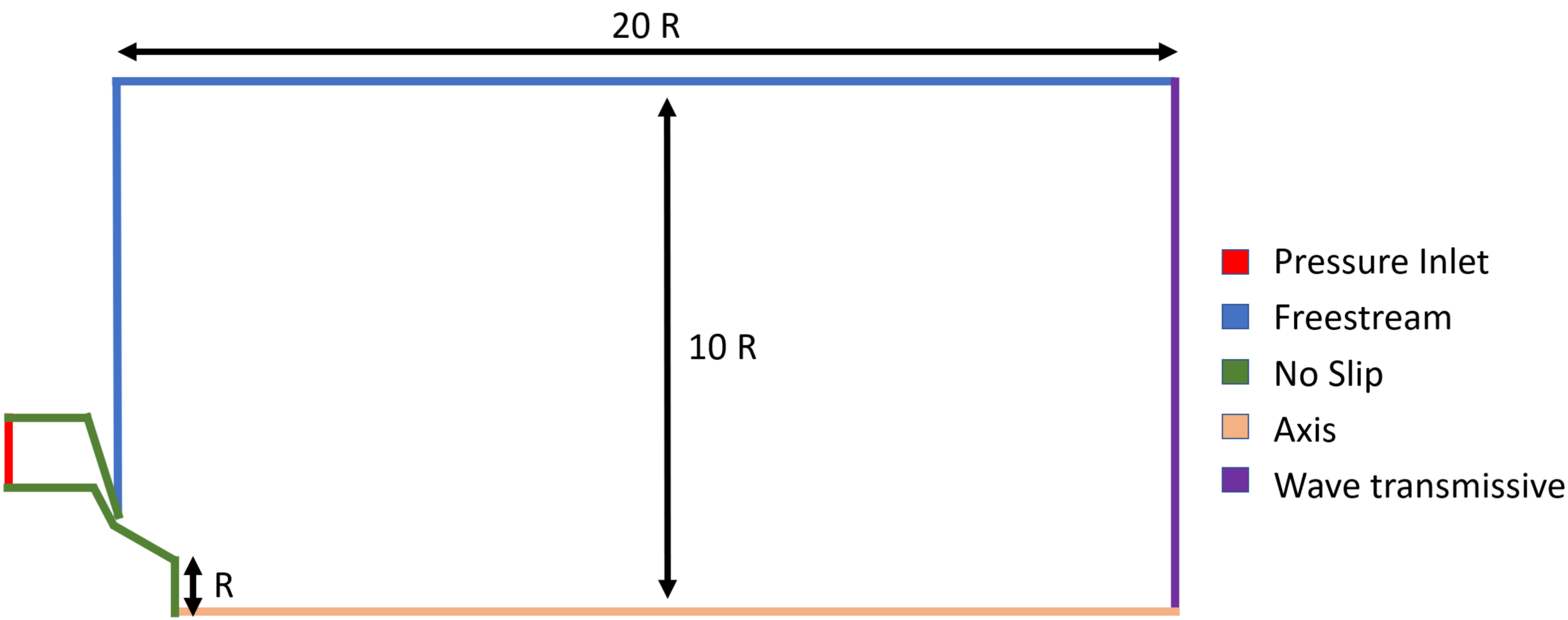
$$h_3(s) = h_2(s)\left[\frac{r^{\frac{5}{4}} \int_0^s \beta^{\frac{5}{4}} \rho_\infty U_\infty \mu_\infty^{-1} ds}{\int_0^s (r\beta)^{\frac{5}{4}} \rho_\infty U_\infty \mu_\infty^{-1} ds}\right]^{1/5}$$

Computational Fluid Dynamics

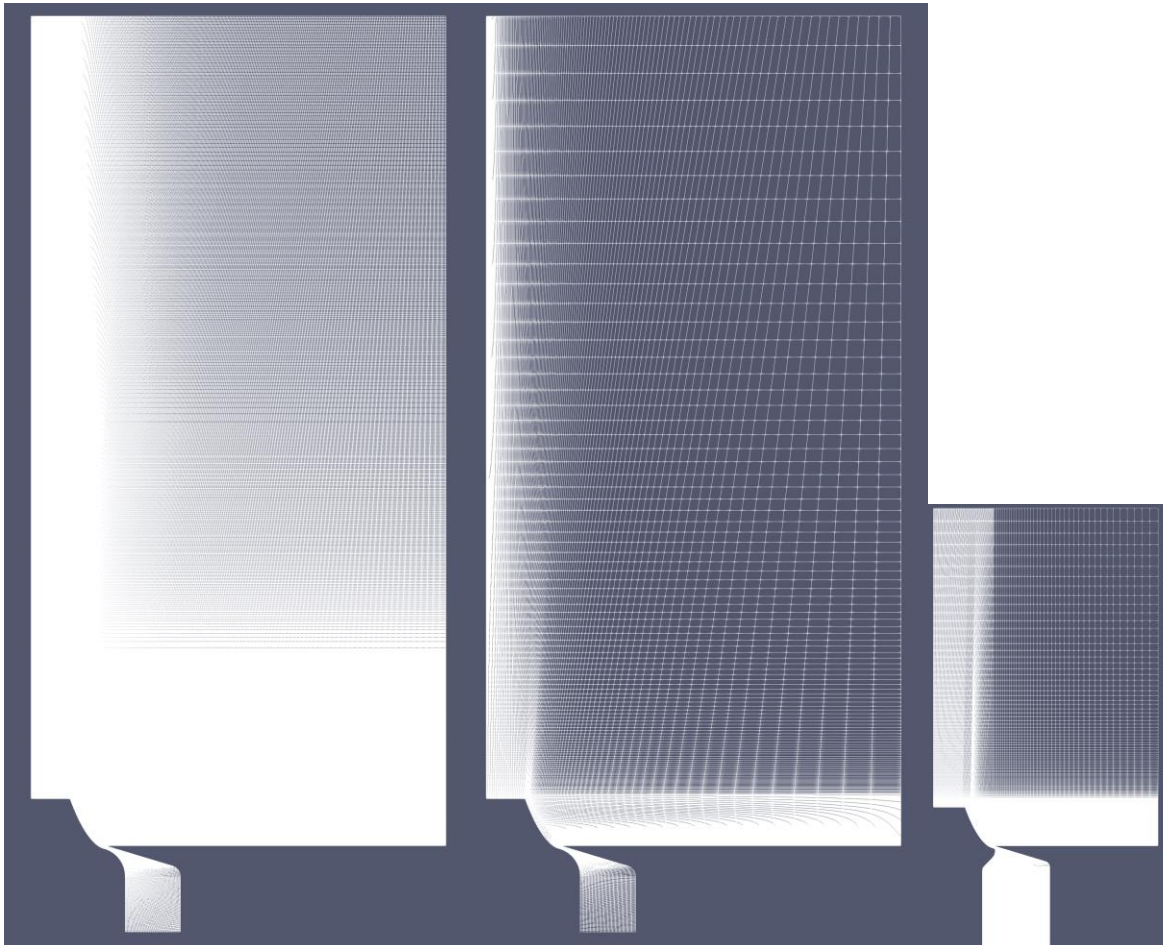
- **rhoCentralFoam:** OpenFOAM Density-based compressible flow solver
  - Based on central-upwind schemes of Kurganov and Tadmor
- **Turbulence Model:** $k - \omega\ SST$
- **Time Step:** $1e^{-10}$ s (Co = 0.5)
- **Total Time:** 10 ms

- **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



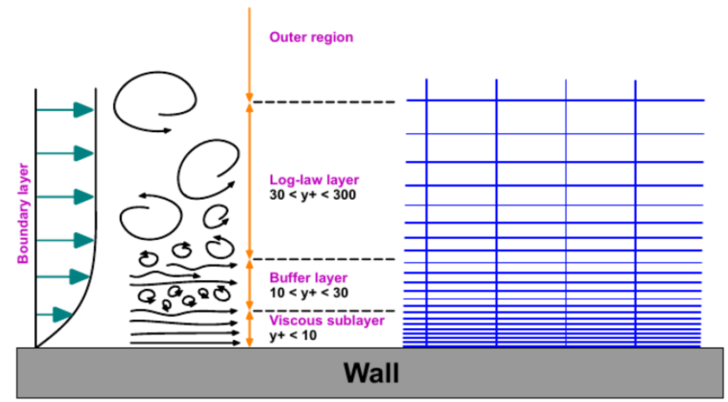
Mesh Independent Solution

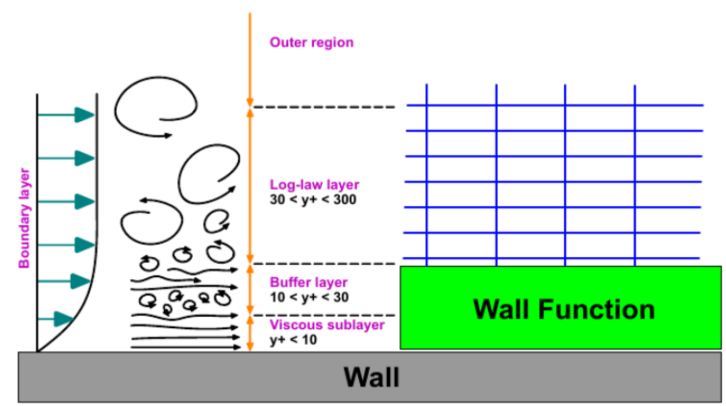


Near-wall modelling

$$y^+ \equiv \frac{yu^*}{\nu}$$

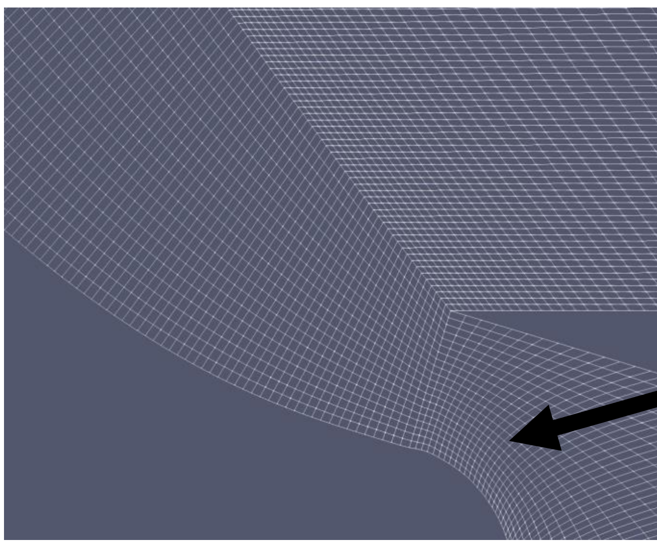
- Low-Reynolds-number modelling (Low-Re)
  - Height of first cell ~ $y^+ = 1$
  - Unaffordable cost
- Wall Function Theory
  - Low cost and good accuracy

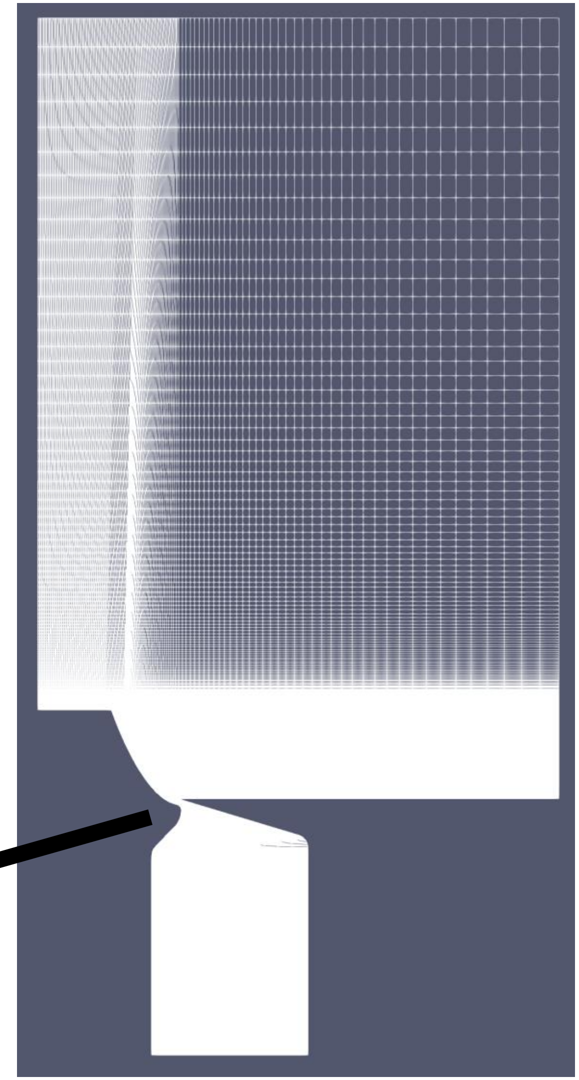




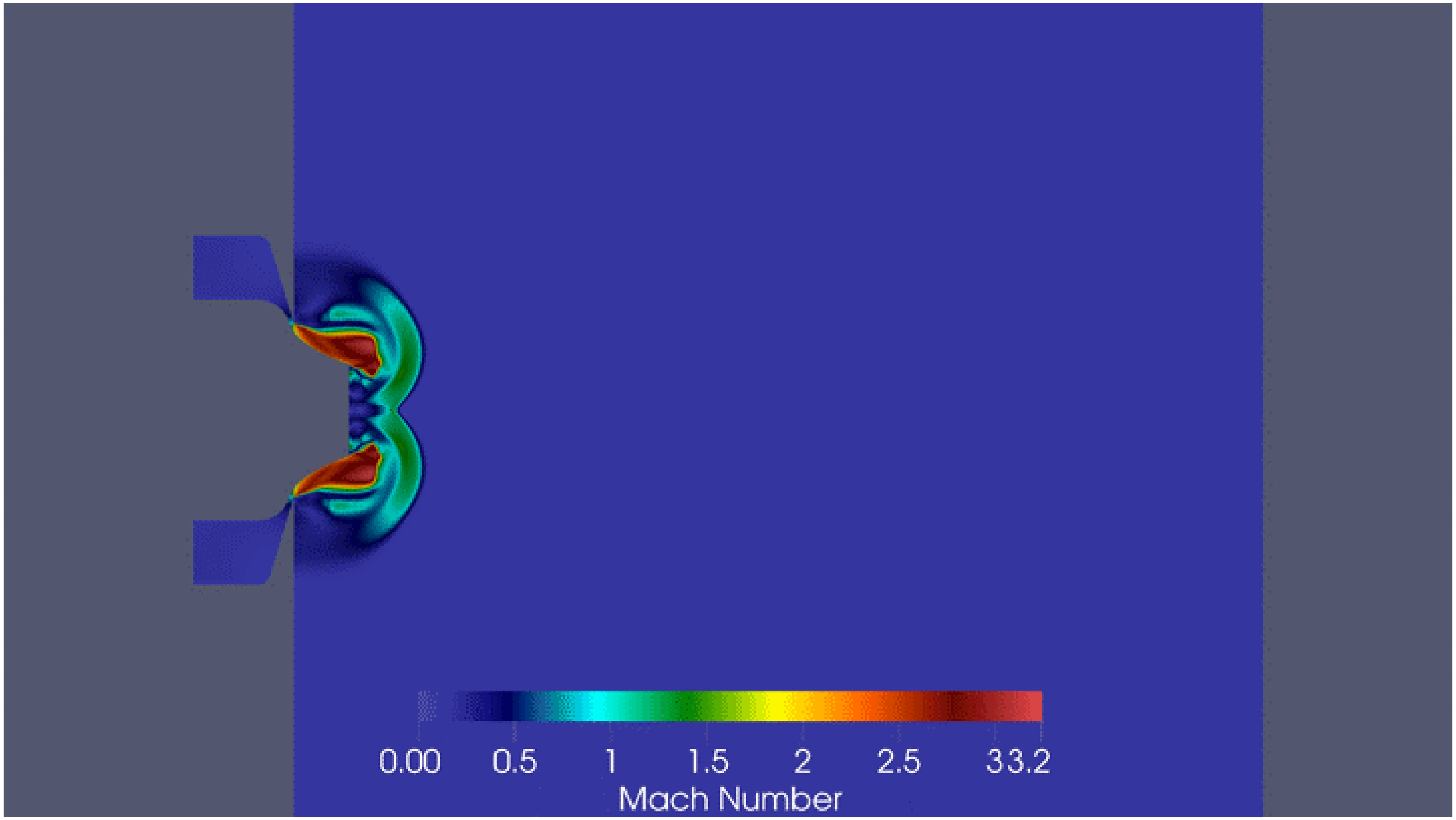
Final Mesh

- Mesh:
    - 2° wedge
    - 76,920 elements





CFD Simulation Results



https://youtu.be/DxzFGrtheIQ

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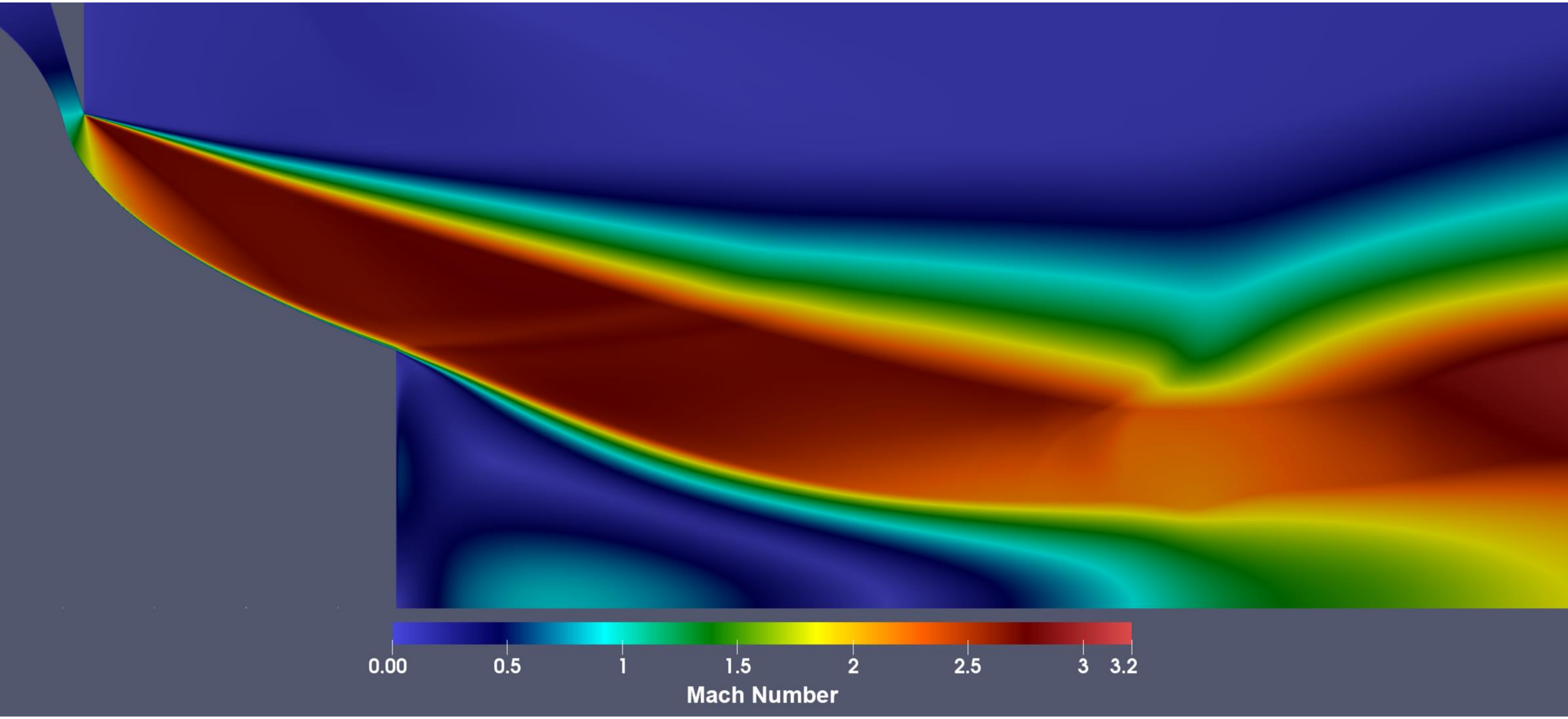

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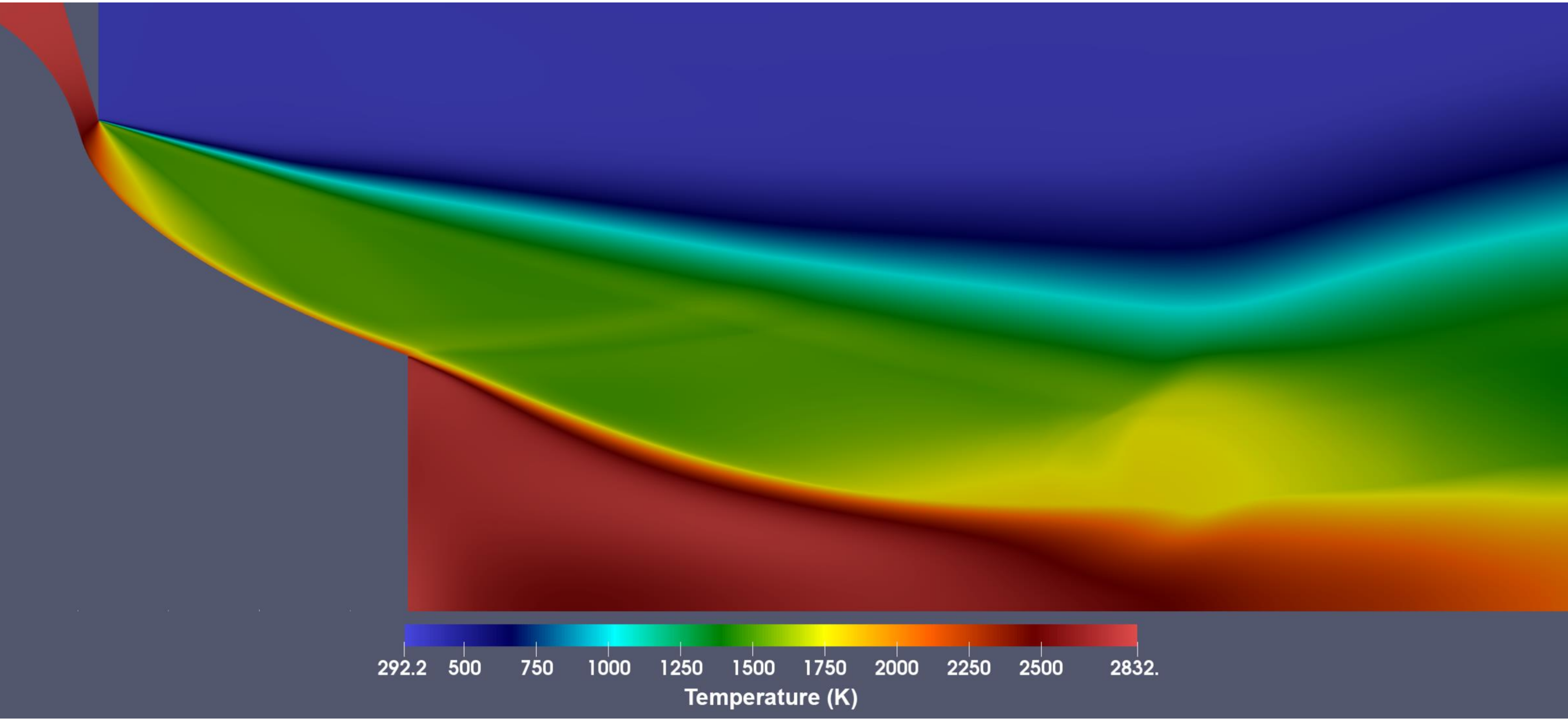
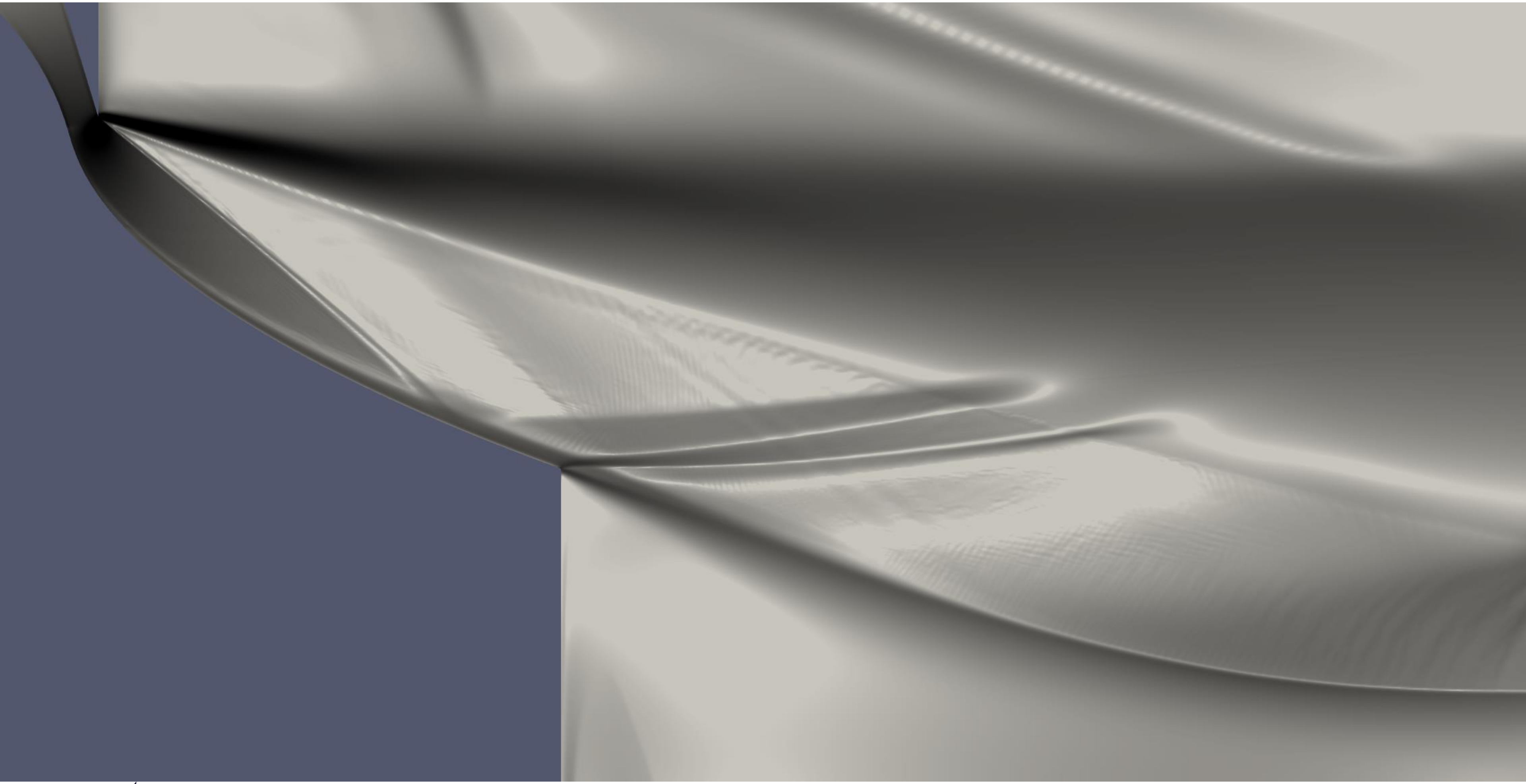


CFD Simulation Results - Schlieren Diagram



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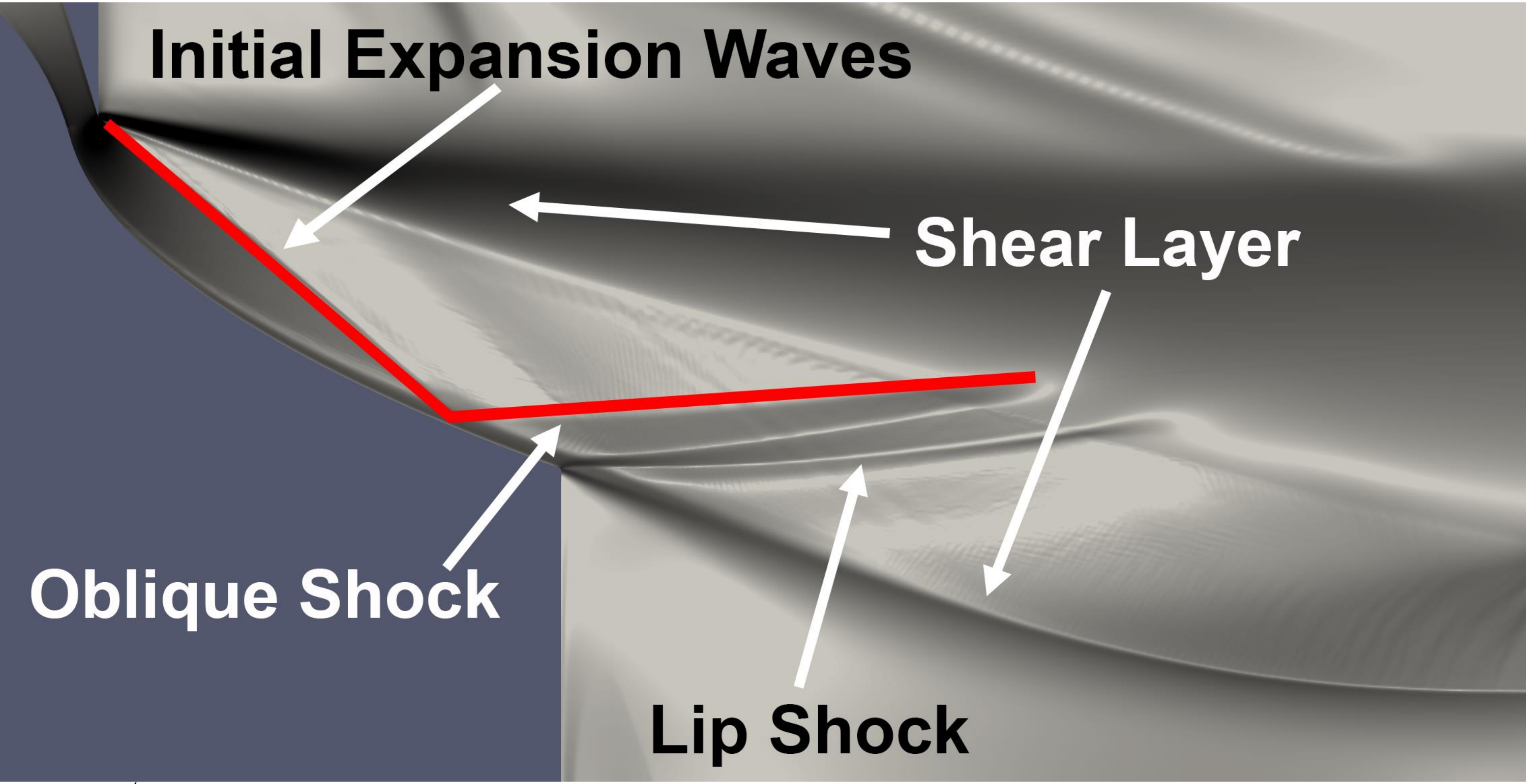
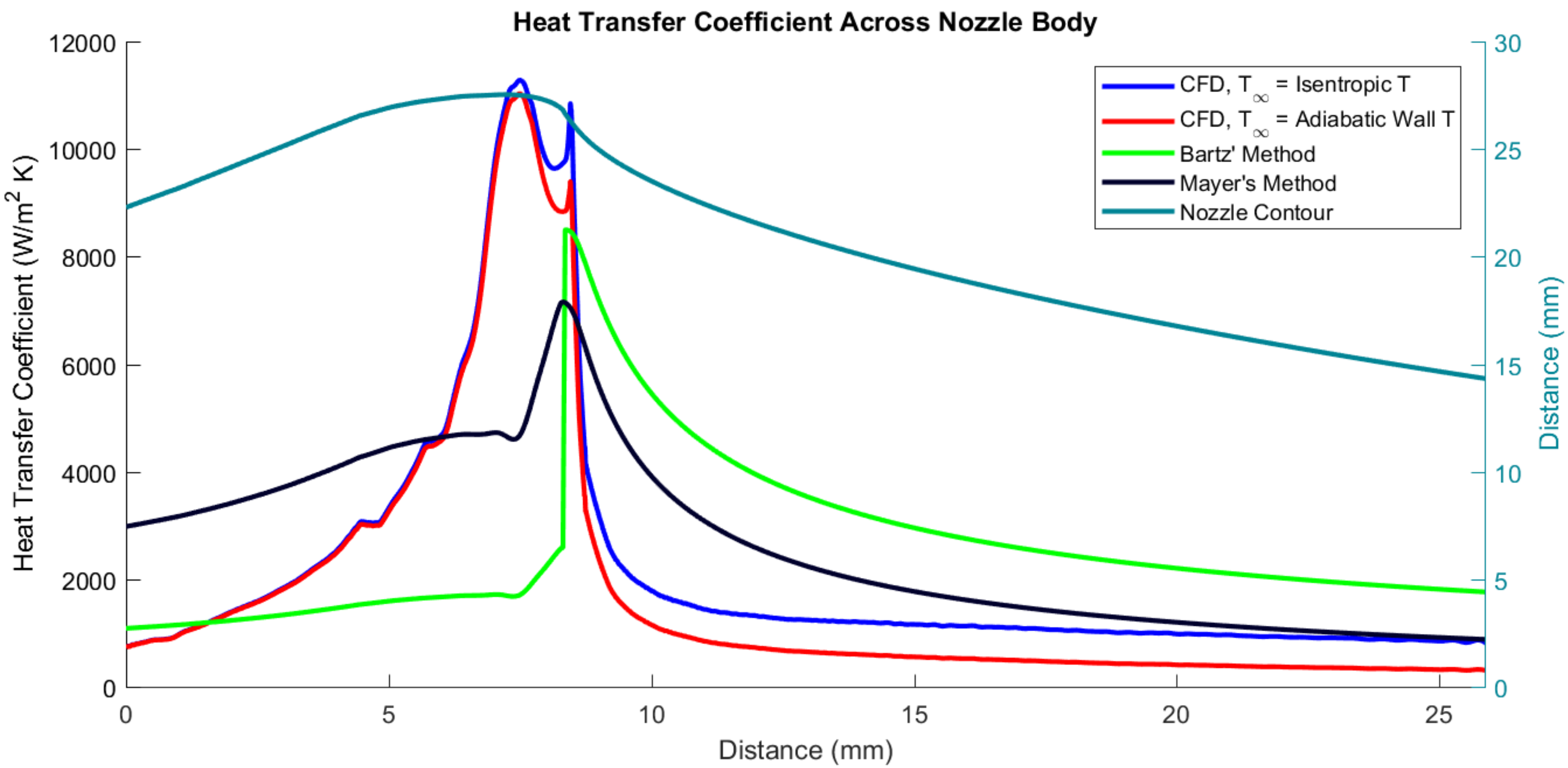
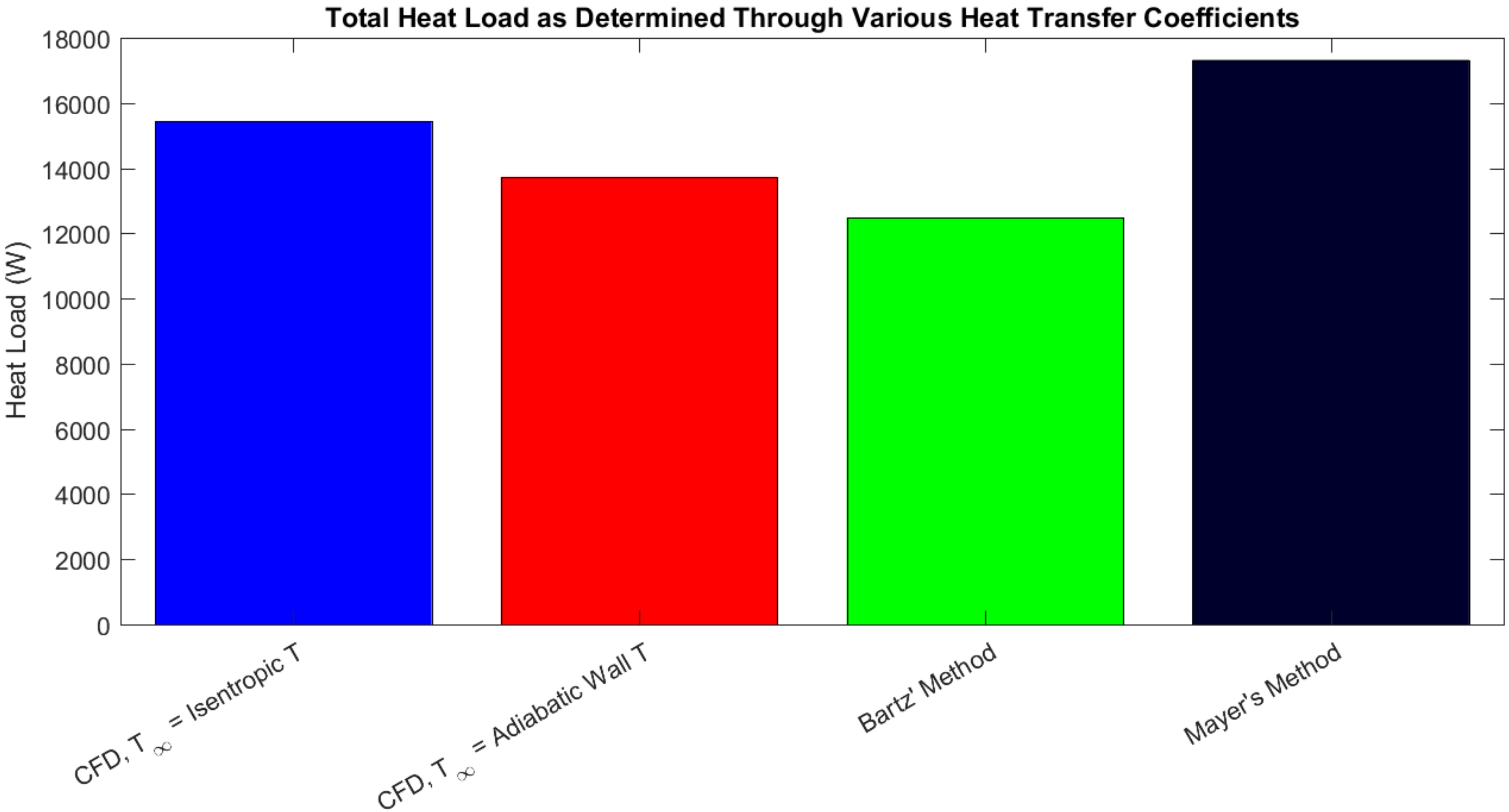


Heat Transfer Coefficient – Results



Total Nozzle Heat Load



Conclusion

- CFD simulation demonstrated that converging section geometry is important to consider as it can lead to increased heat load
- Both Bartz' and Mayer's Methods prove effective for heat load prediction
  - Mayer's is more conservative and so is chosen for future design efforts

QUESTIONS?

Emerson Vargas Niño
Rocket Propulsion Lead