Numerical Design of Plug Nozzles for Micropropulsion Applications

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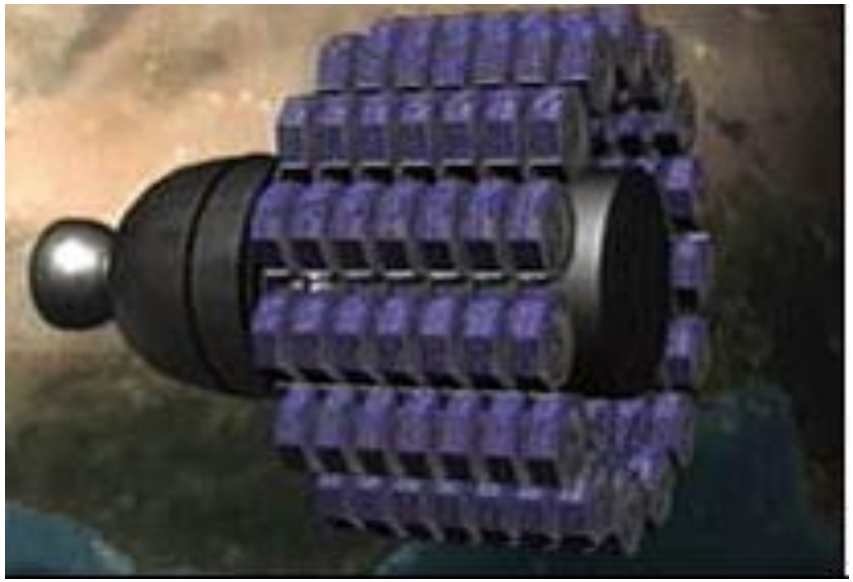
Vermont Advanced Computing Core

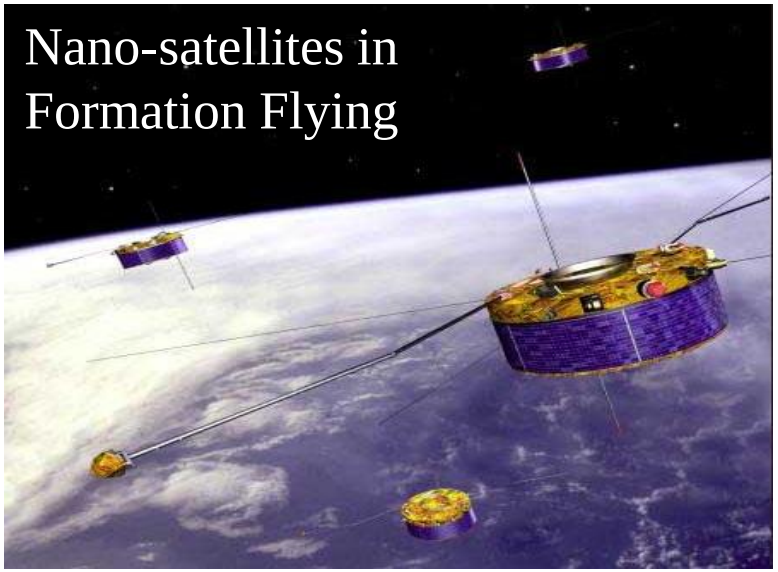
at The University of Vermont.

Why Micro-Propulsion ?

- Advances in MEMS manufacturing spawned new classes of satellites
  - Micro-satellites (**<100kg**), nano-satellites (**<10kg**) cube-sats (10x10x10cm)
- Allow new missions impossible with traditional satellites.
  - Precision Formation Flying - large baseline for optical missions.
  - Low cost commercial and academic access to space (reduced payload mass)
- Small satellites require properly scaled propulsion systems for station keeping

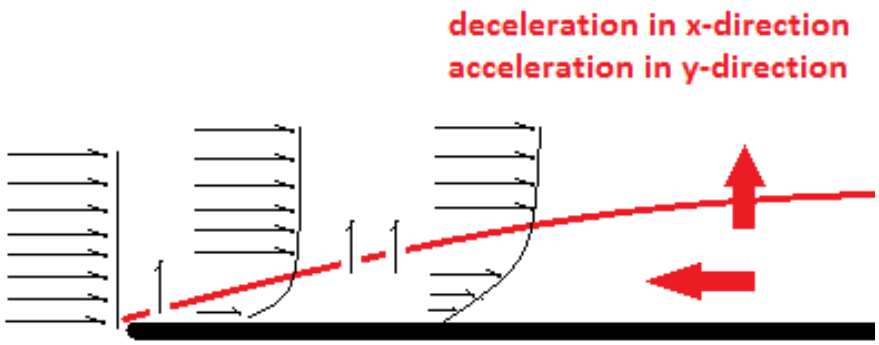
→ ***Microthrusters***

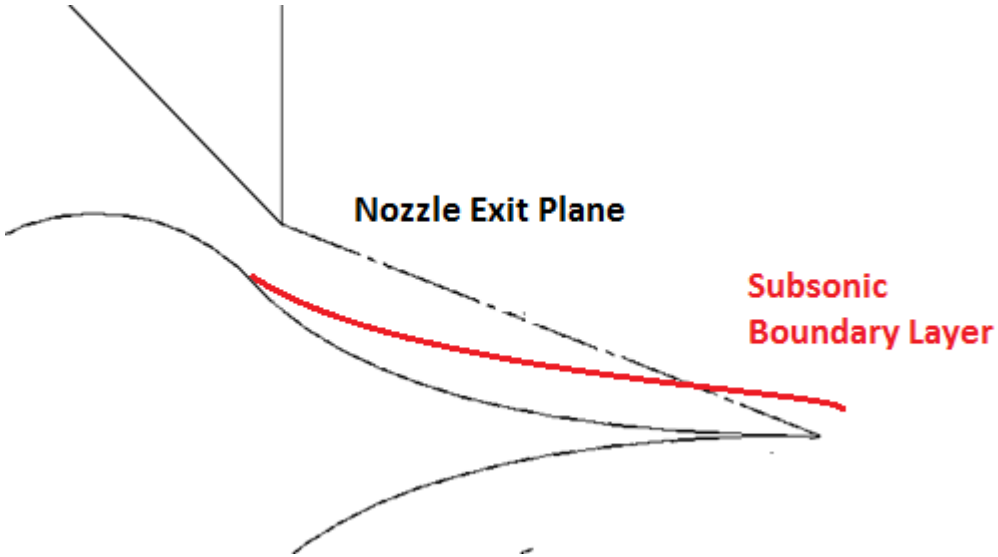




Why Develop Micro-Nozzles?

- Microscale nozzles encounter a **fundamentally different** flow regime
  - viscous supersonic flow: Re<1000, 1<Ma<5
- Result: macroscale designs yield poor performance when scaled down for micropropulsion systems.
- The development of nozzle specifically designed for the microscale can substantially increase microthruster efficiency.
- For satellites this can:
  - Reduce required fuel budget / increase satellite life span
  - Reduce propellant tank volume (increase free space / reduce weight)
  - Increase propellant options
  - Reduce costs





Design Challenges

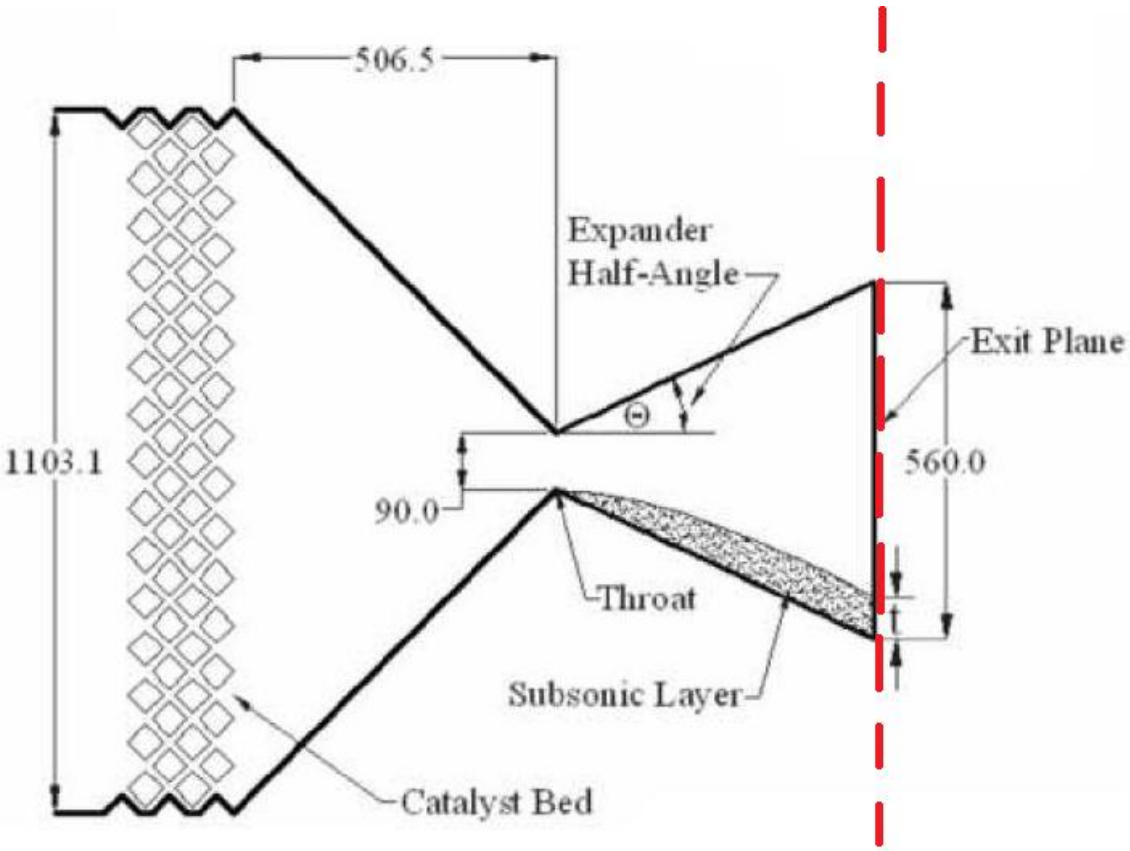
- Increased wall surface area to volume flow ratio
  - Increased viscous effects → large subsonic boundary layer
  - Increased wall heat transfer effects (fanno flow effects)

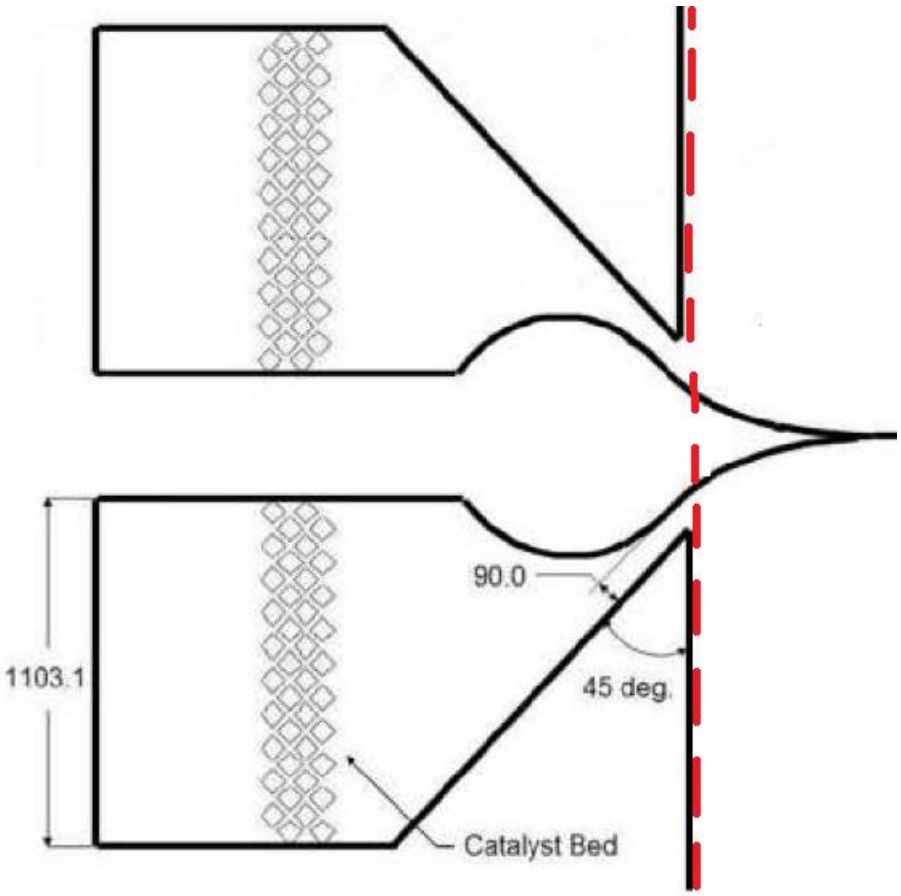
- MEMS Manufacturing Constraints
  - 2D pattern etched down to create 3D nozzle (rectangular cross-section)
  - **DRIE** >100μm
  - Advances in 3D printing → axisymmetric designs

- 3D Effects
  - Viscous effects on cover-plate
  - Corners rectangular cross-section

- Difficult to obtain accurate measures of thrust experimentally
  - Sensor noise can be appreciable in magnitude compared to thrust being measured
  - Specially designed thrust stand + vacuum chamber
  - Few micropropulsion thrust stands exist: nNTS (UCCS)

Bound vs. Unbound Regions





(Left) ***UVM & NASA/GSFC***

(Right) ***Plug geometry of this study***

- Red line represents the extent of the cover plate in the axial direction.
- Black lines represent 2D pattern etched into substrate.

Advantages of Plug Nozzle on Microscale

California State University, Long Beach (CSULB), in partnership with Garvey Spacecraft Corporation (GSC), successfully conducted a static fire test of a 1000 lbf ablative annular aerospike rocket engine in the Mojave desert on June 21, 2003 using LOX and ethanol propellants.

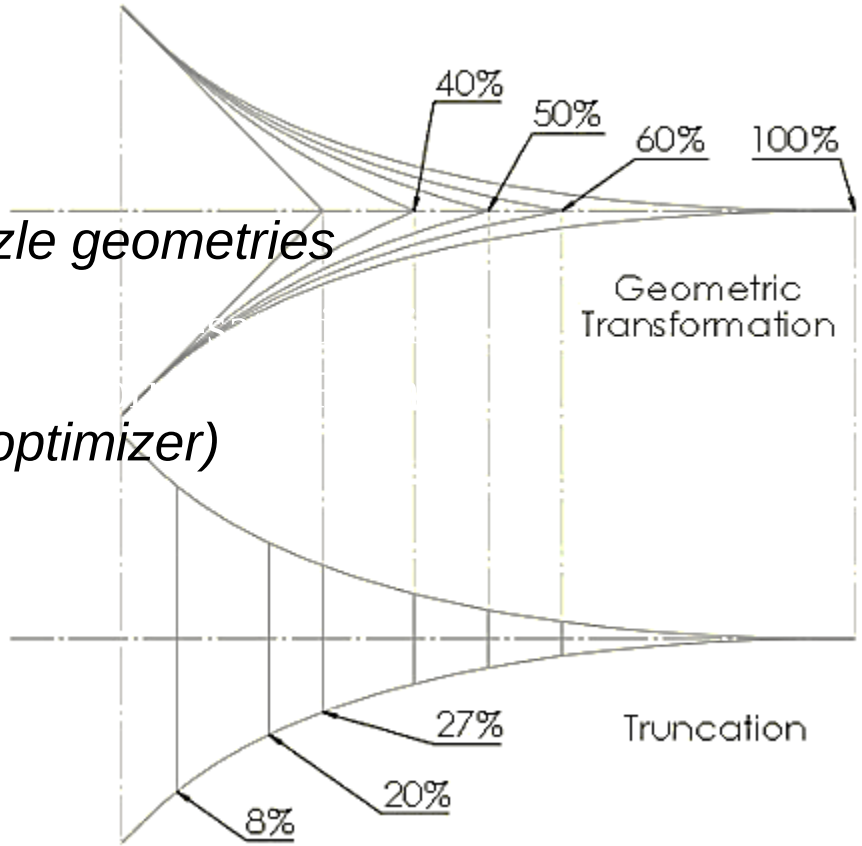
- Lower surface area reduces viscous losses
- Altitude Compensation Effect may improve performance at startup / shutdown portions of duty cycle
- Thrust Vector Control (TVC)
- Minimal Transverse Losses
  - not a true expansion fan
  - no expander angle losses
- Reduced “cover plate” and “corner” losses

Area of Research and Projects

Research Focus

Design and analysis of plug nozzles for micro-propulsion application

- ***Current Projects***
  - *Scaling effects on numerical thrust calculation*
  - *2D parametric plug shape design study*
  - *3D analysis of plug nozzle flow field*
  - *3D comparison to conventional micronozzle geometries*
- ***Future Projects***
  - *Plug contour optimization (coupled CFD-optimizer)*
  - *Axisymmetric geometries*

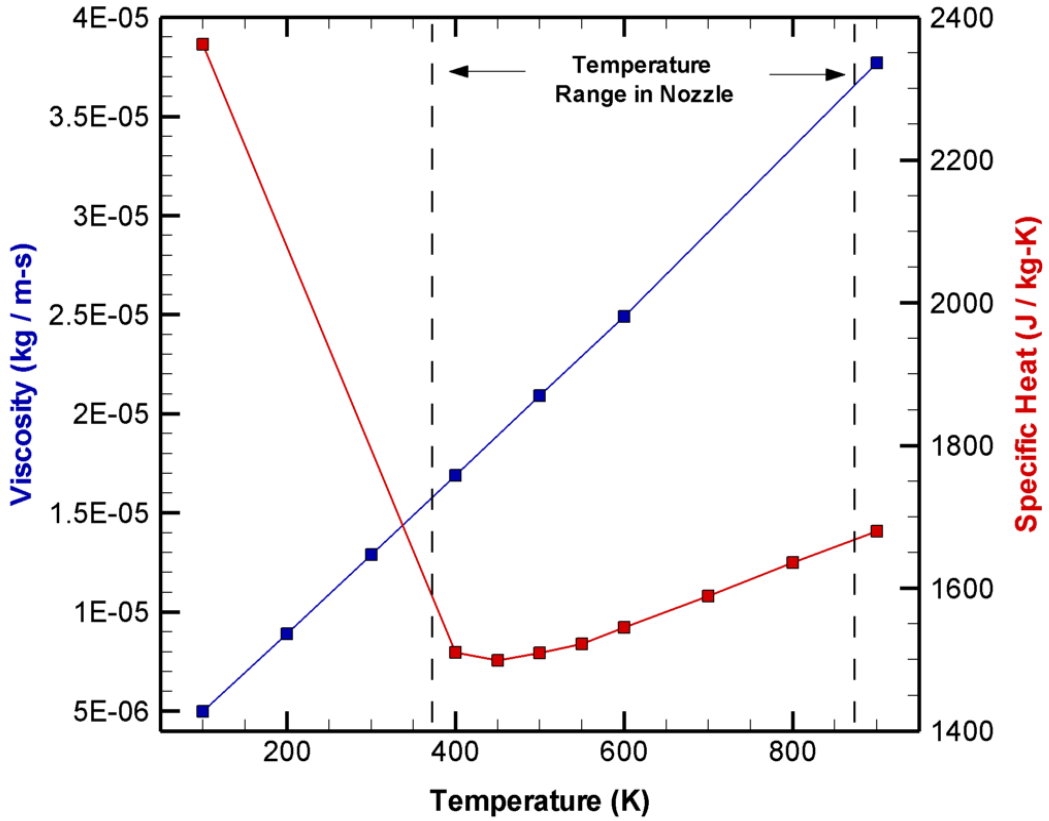


Numerical Model Overview

- **Steady, Laminar, Compressible Navier-Stokes Equations**
- **Ideal Gas Assumption** (Equation of State)
- **OpenFOAM** rhoCentralFoam solver (density based compressible flow solver)
- **Working Fluid Mixture = $H_20 + O_2$ (85% Pure High Test Peroxide) = *Frozen Flow**
  Temperature dependent thermo-physical properties

  - **Specific Heat: 6th order polynomial**

    (valid range: 100 – 2,000 K)
  - **Viscosity: 1st order polynomial**
  - **Thermal Conductivity: Constant**



Mesh Sizes

- 2D ≈ 200,000 cells
- 3D ≈ 3,000,000-8,000,000 cells

*** NASA-Glenn (CEA)**
Chemical Equilibrium Program
McBride, B. & Sanford, G

Boundary Conditions

Inlet Boundary

- **Stagnation Pressure** — $25\ kPa < P_0 < 250\ kPa$
  - **Reynolds Number (throat)** — $80 < Re\ No. < 800$
  - ***Pressure Ratio*** — $25 < PR < 250$
- **Stagnation Temperature** — $T_0 = 886\ K$ (*adiabatic flame temperature*)

Constant Pressure Outlet

- **Ambient Temperature** — $T_\infty = 300K$
- **Backpressure** — $P_\infty = 1.0\ kPa$ *(maintain continuum flow regime)*

Mach No. < 1 **-** Constant pressure outlet imposed

Mach No. ≥ 1 **-** Flow interior extrapolated to boundary *(method of characteristics)*

Adiabatic Nozzle Walls

- **No–Slip**

Assessing Performance: Thrust Calculation

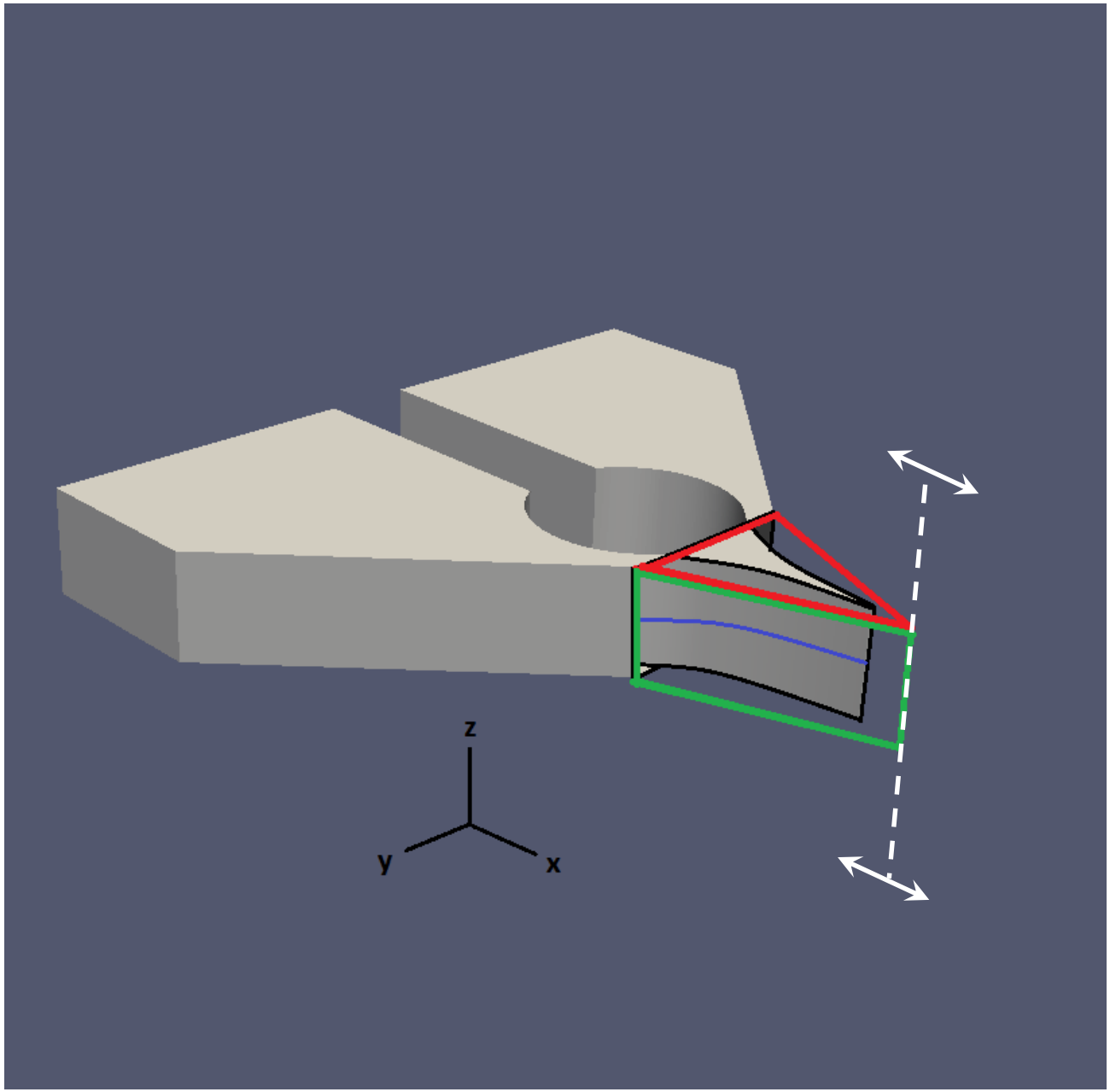
How can the accuracy of a thrust calculation method be assessed?

Thrust should be independent of the sample plane location. (conservation of momentum)

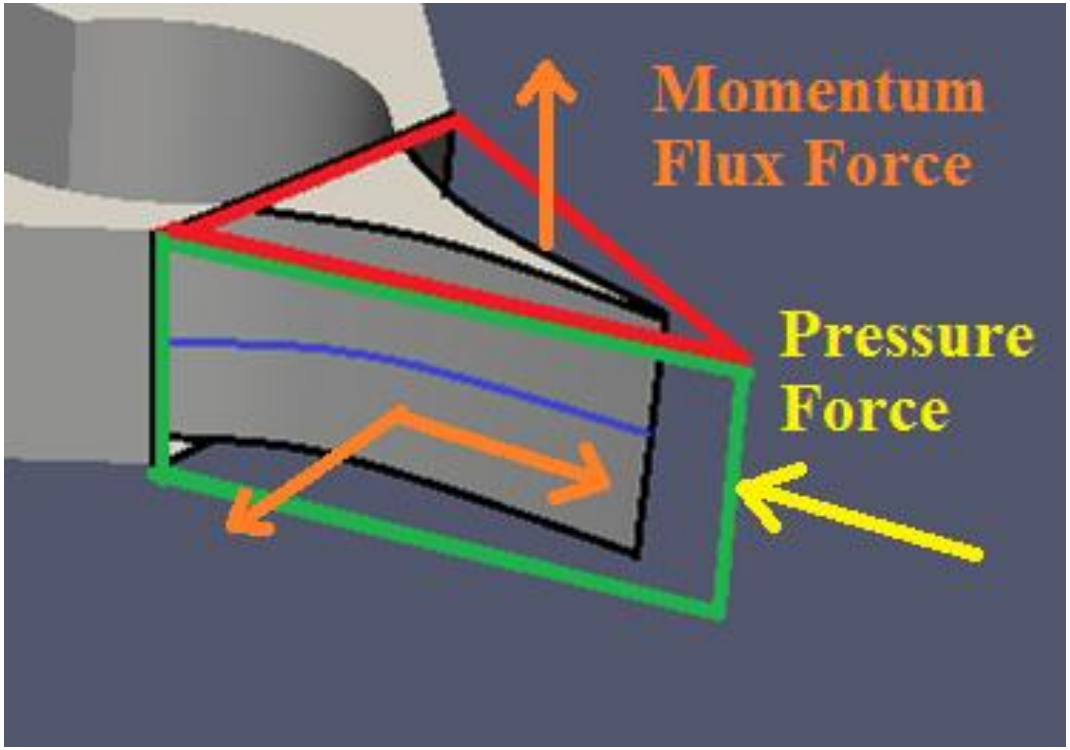
Assess the spatial dependence of the thrust calculation

RED: etch-normal plane
GREEN: tip-lip plane

(1) Increase height of etch-normal plane in the z direction.
(2) Extend tip-lip plane to form close domain



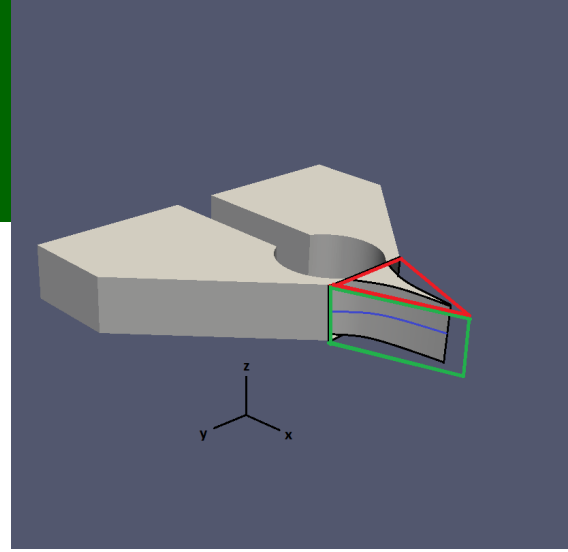
Traditional Thrust Calculation

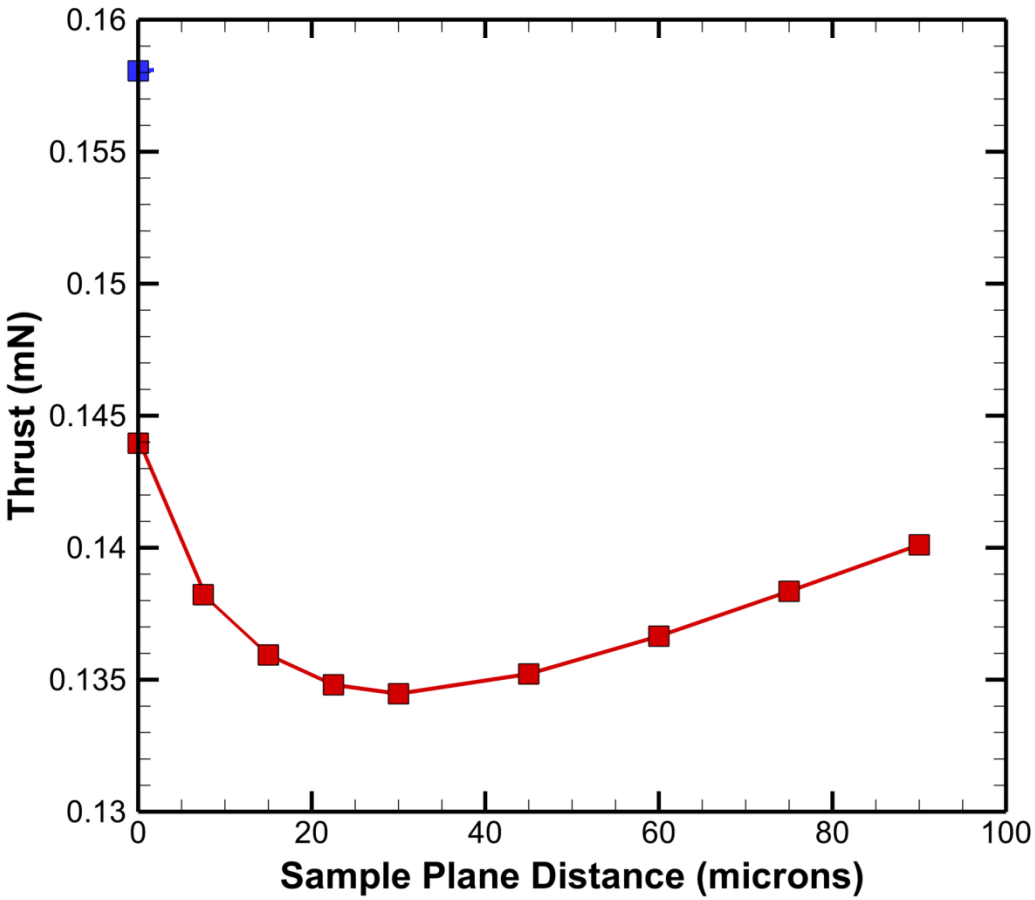


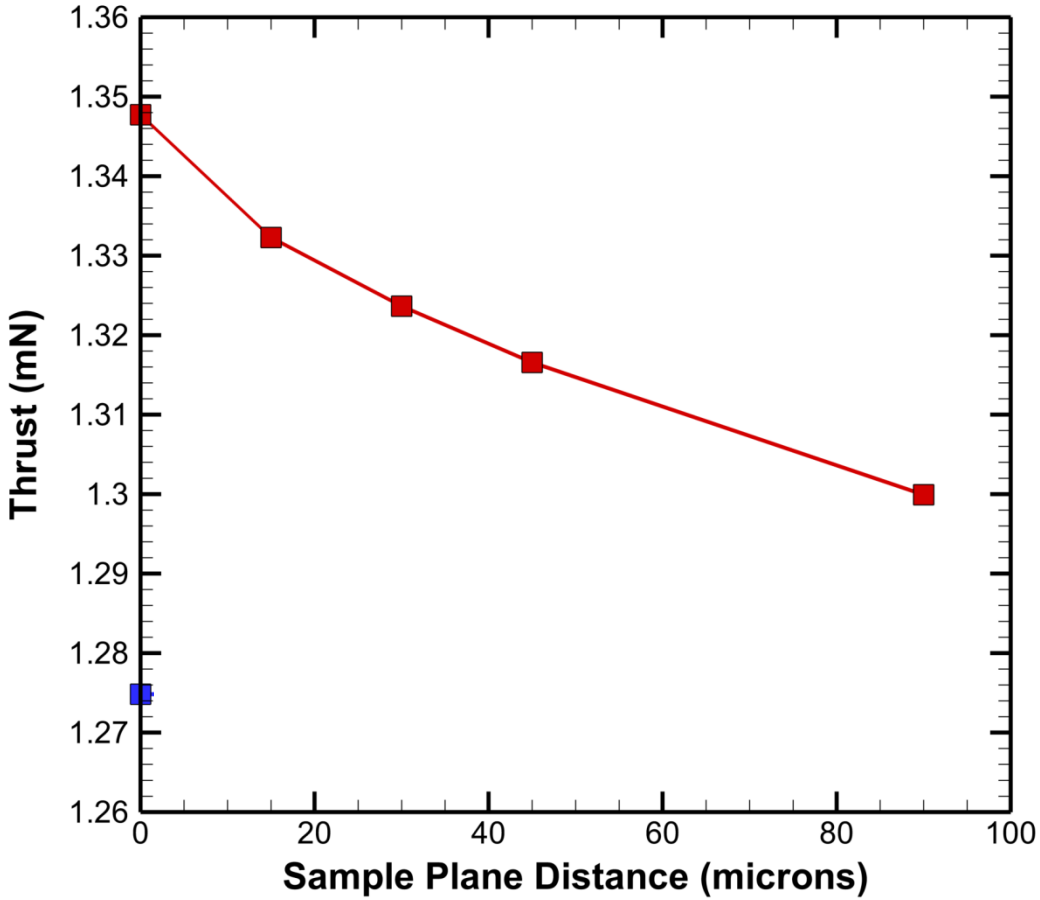
Thrust Calculation

$$\boldsymbol{F} = \int_{A_e} \rho \boldsymbol{U}(\boldsymbol{U}\cdot\boldsymbol{n})dA + \int_{A_e} ((p - p_\infty)\cdot\boldsymbol{n})dA$$

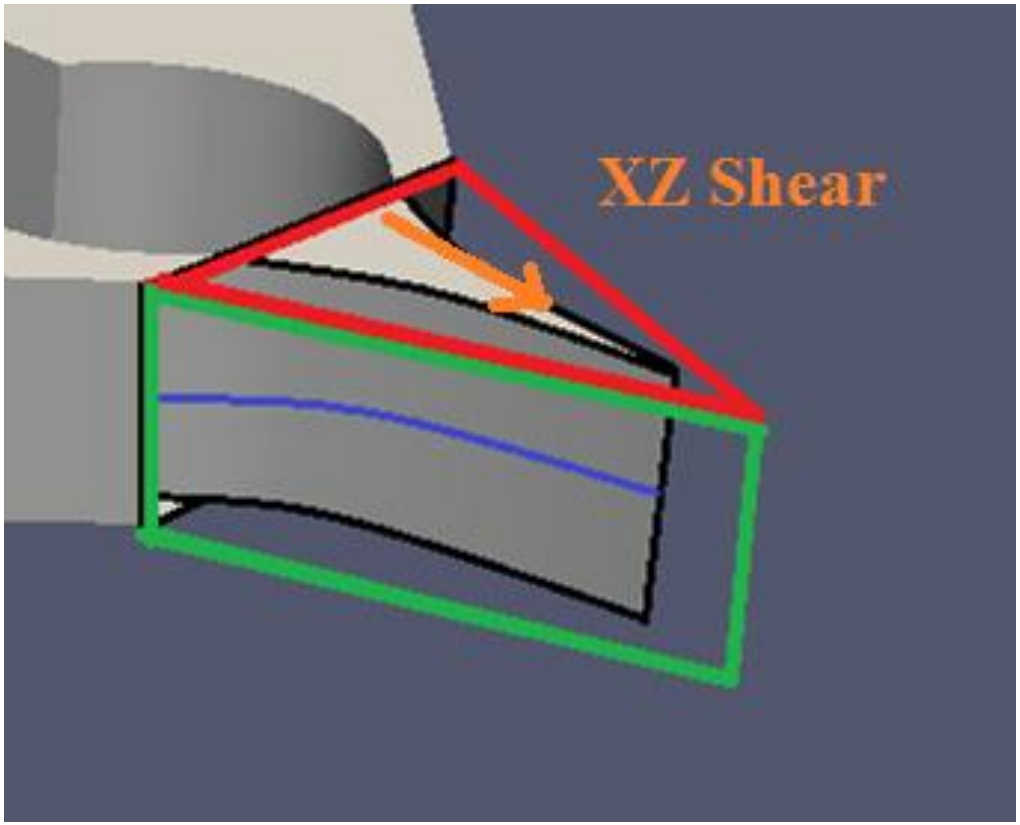
Momentum Flux **Pressure Imbalance**



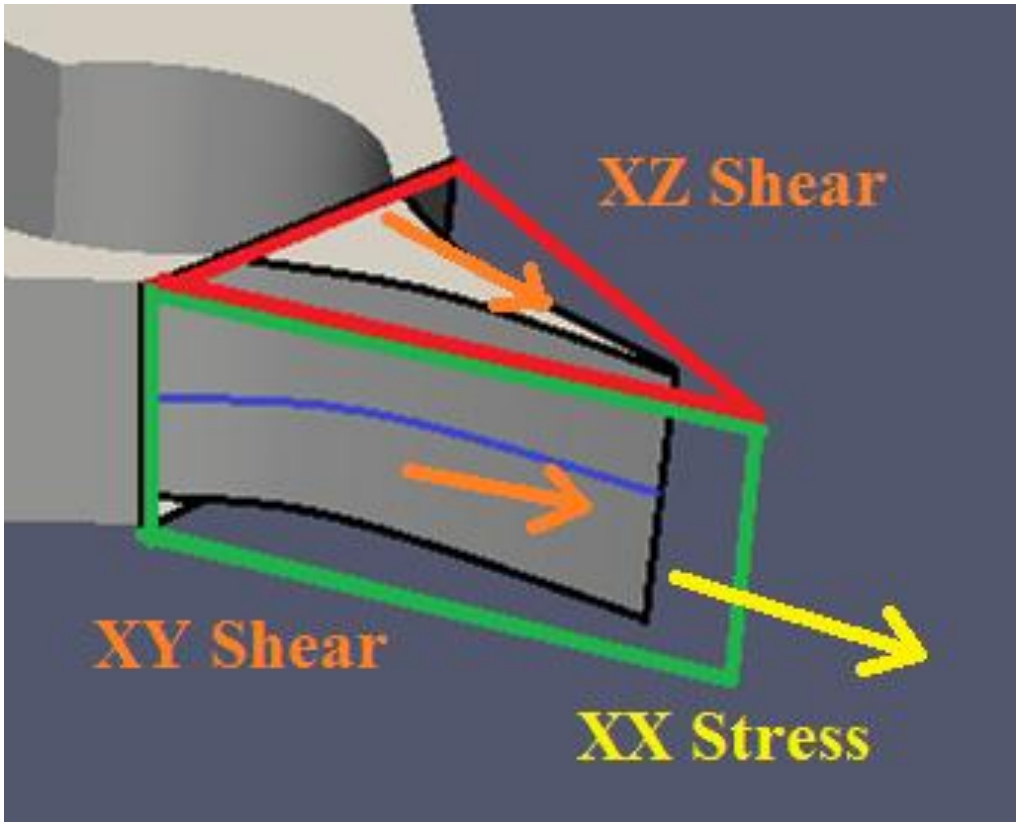




Thrust Calculation Etch-Normal Plane



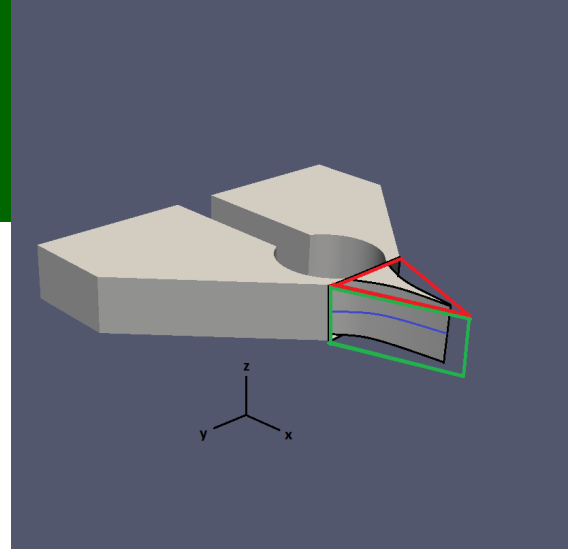
Thrust Calculation Tip-Lip Plane

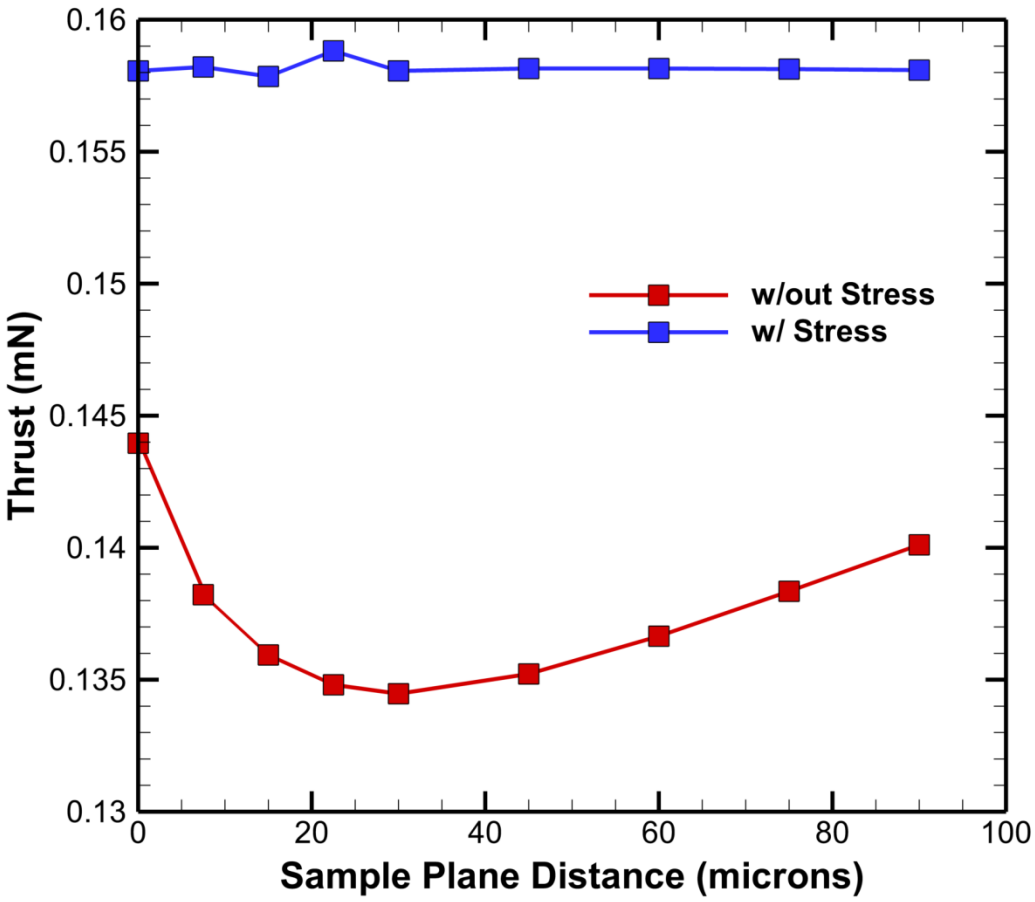


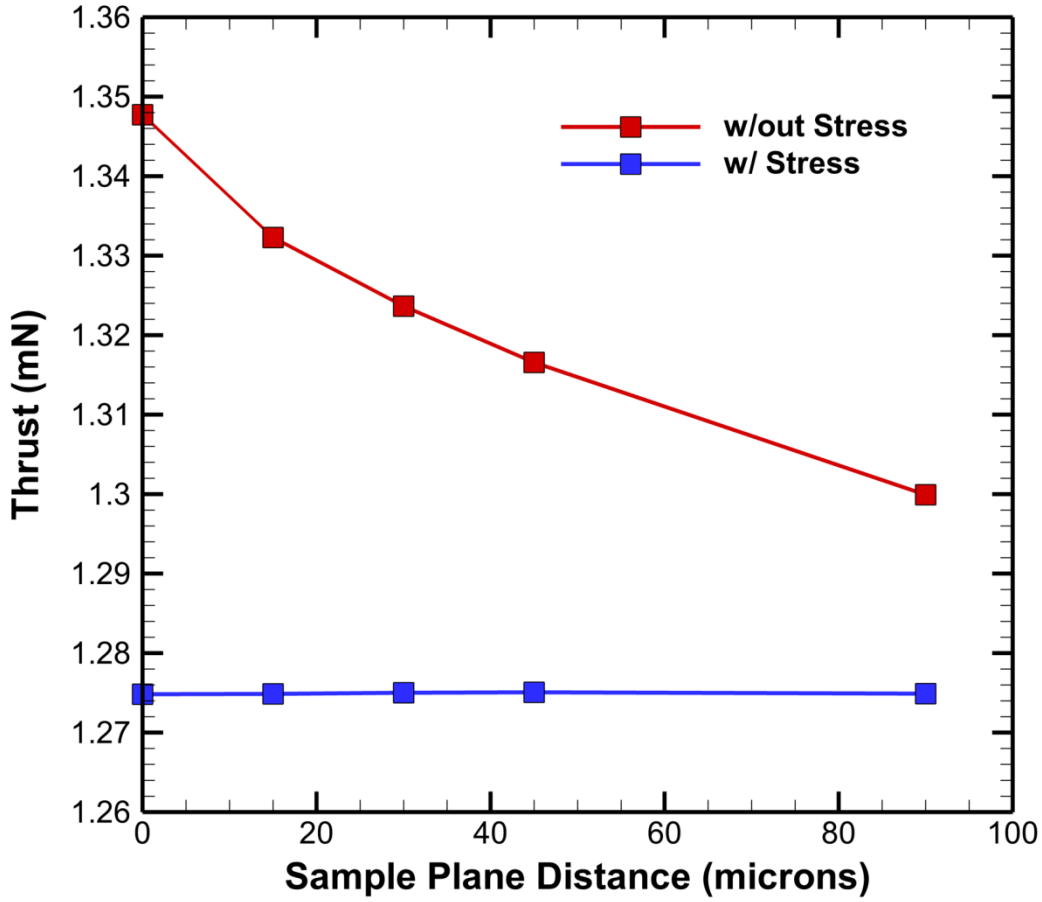
Thrust Calculation

$$F = \int_{A_e} \rho \boldsymbol{U}(\boldsymbol{U}\cdot\boldsymbol{n})dA + \int_{A_e} ((p-p_\infty)\cdot\boldsymbol{n})dA + \int_{A_e} (\boldsymbol{\tau}\cdot\boldsymbol{n})\,dA$$

Momentum Flux **Pressure Imbalance** **Exit Plane Shear**



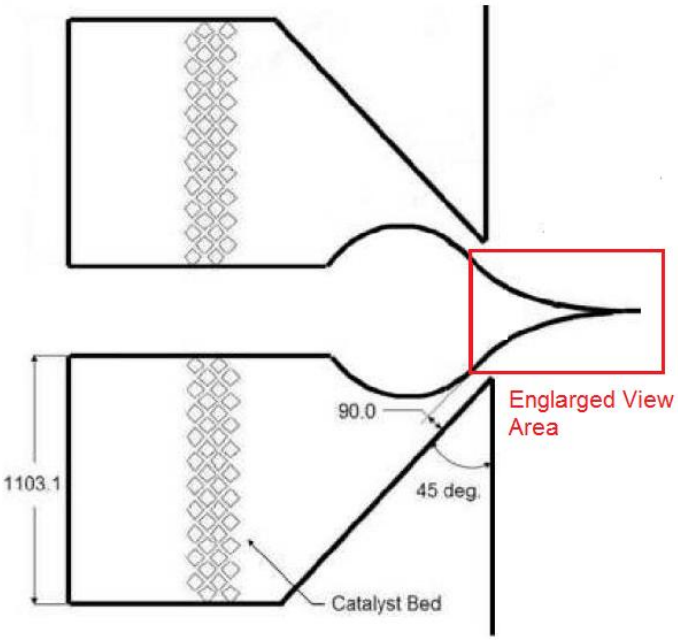


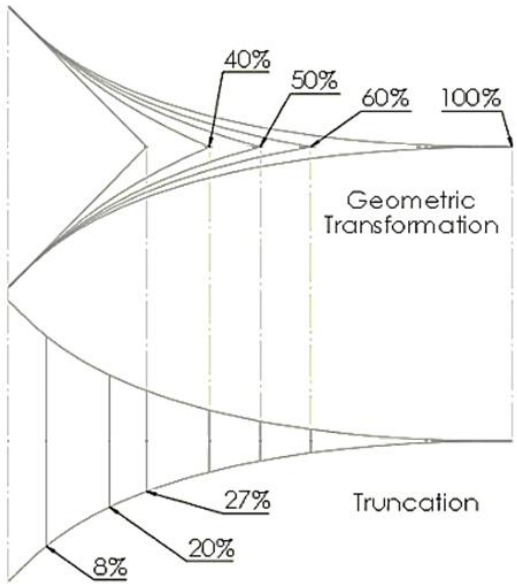


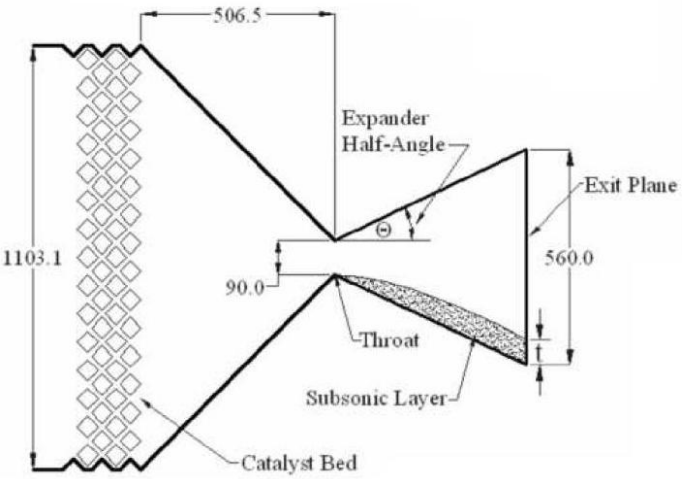
2D Geometric Study

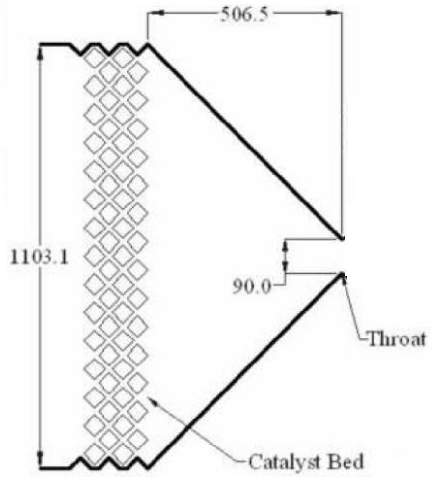
Overview:
Plug nozzle contour shortened via geometric transformation and truncation

Performance compared to the 30˚ UVM-GSFC linear-walled nozzle and a sonic orifice









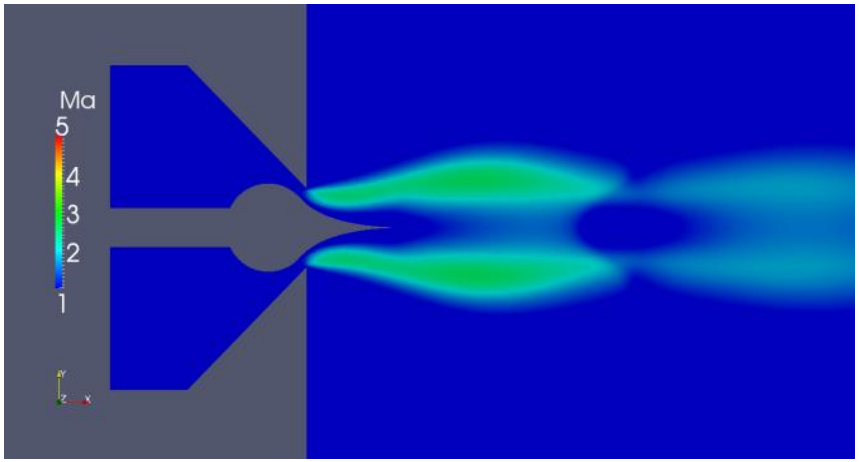
Parametric Design Variables:
Geometry and Throat Reynolds number

Geometries:
Truncation lengths: 8,20,27,40,50,60,70%
Geometric Transformation lengths: 27,40,50,60,70%
Other Geometries: 30˚ linear walled, sonic orifice

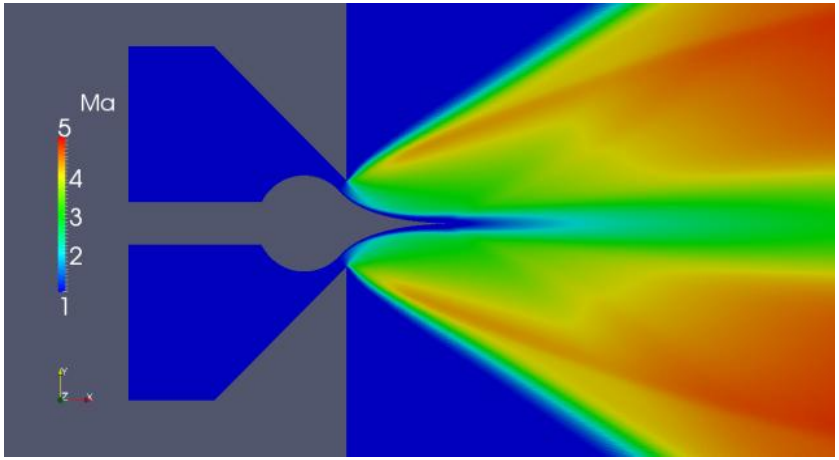
Throat Reynolds Numbers:
80, 160, 320, 480, 640, and 800

Full Length (FL)

Re = 80 (25kPa)

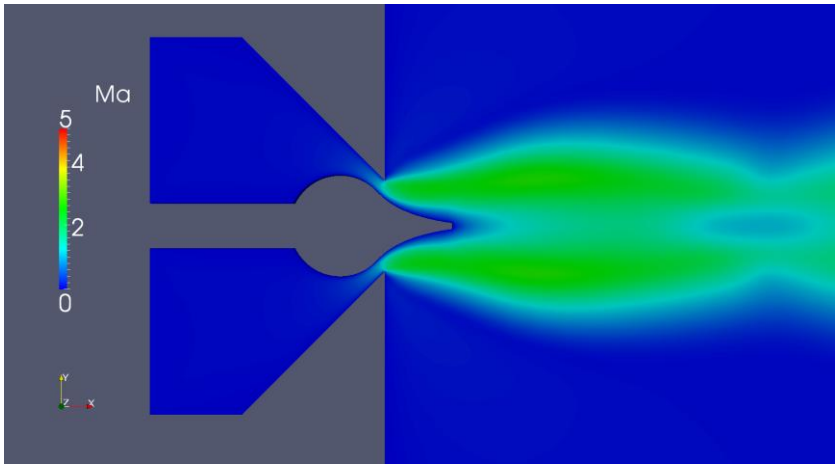


Re = 800 (250kPa)



60% Length

Re = 80 (25kPa)



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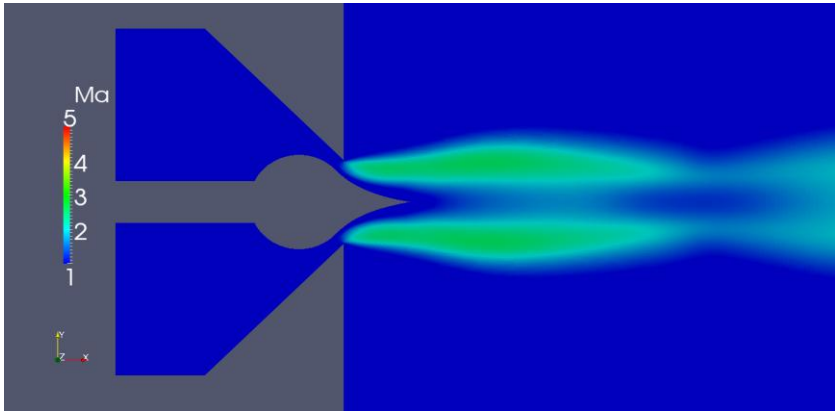
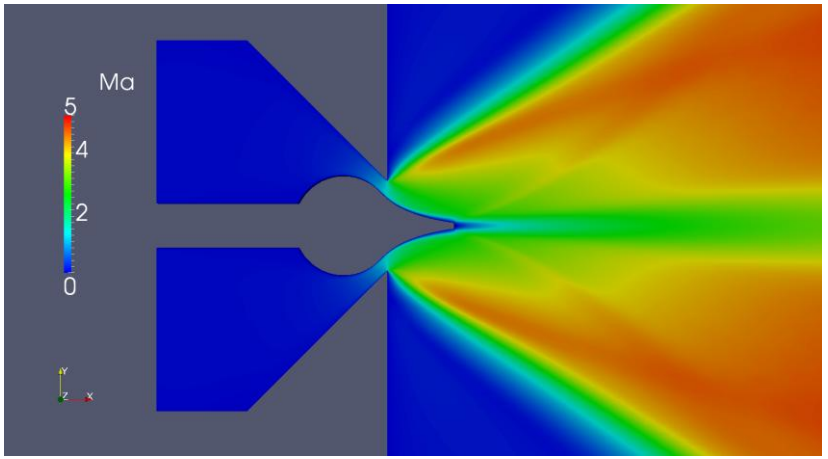


Geo Transformation

Re = 800 (250kPa)



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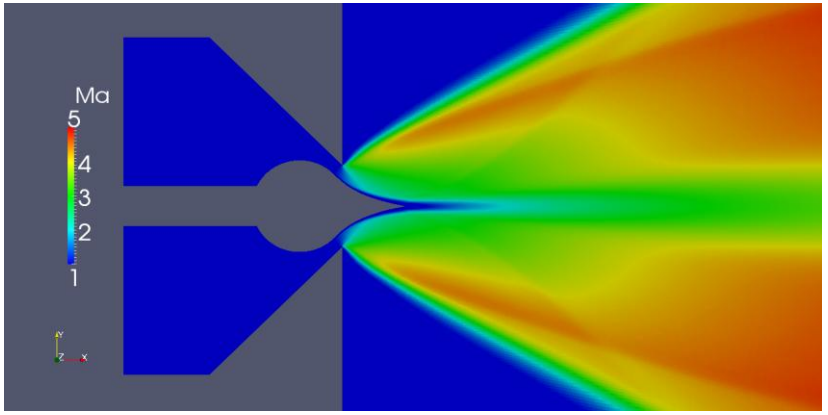
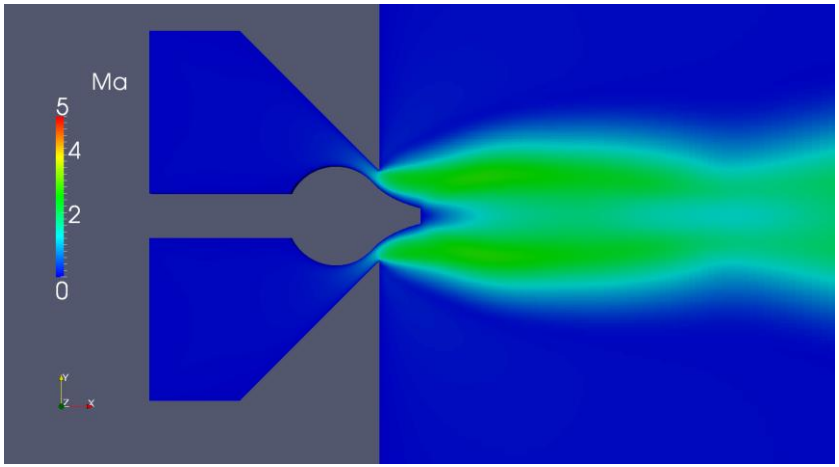


Geo Transformation

40% Length

Re = 80 (25kPa)



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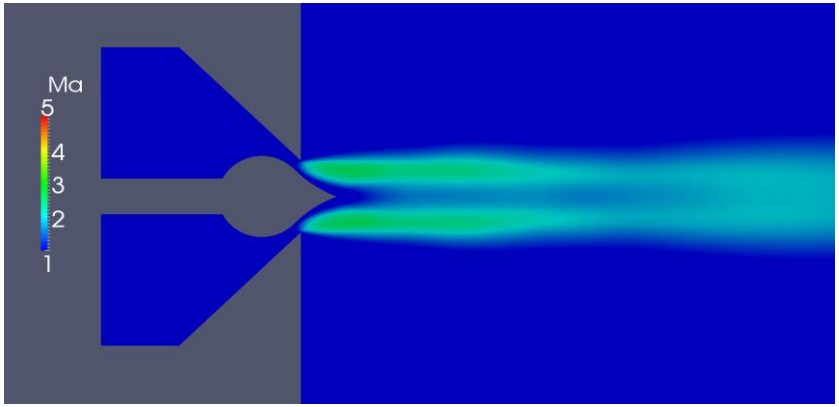
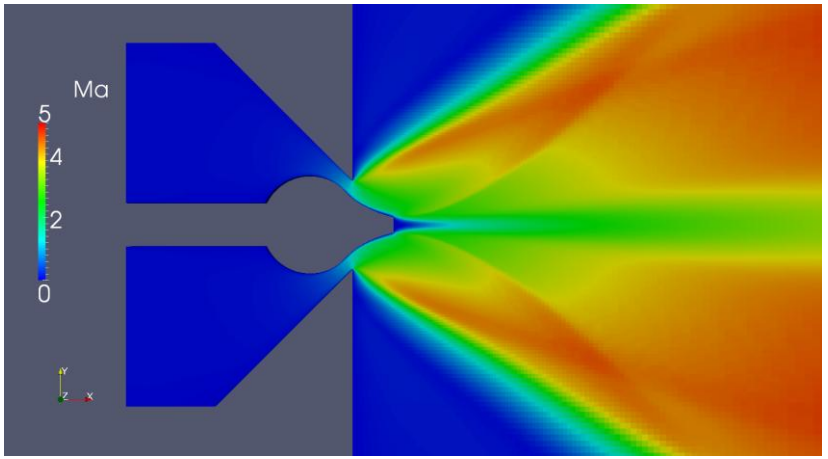


Geo Transformation

Re = 800 (250kPa)



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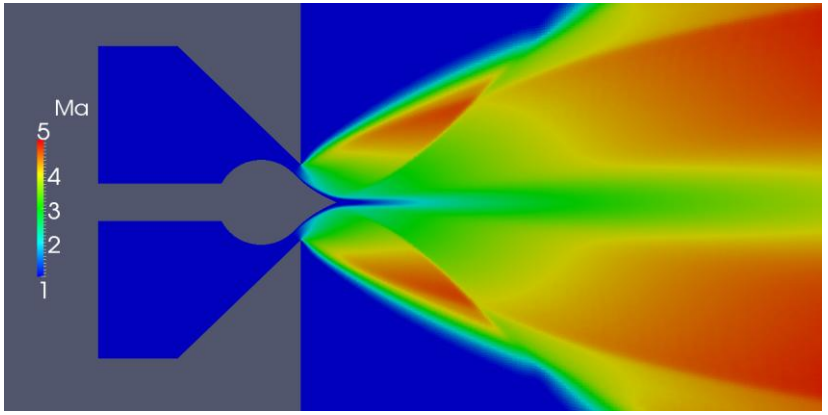
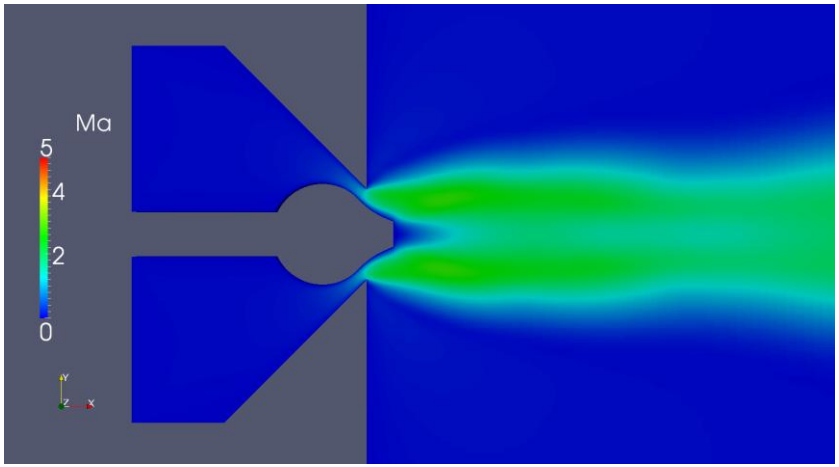


Geo Transformation

27% Length

Re = 80 (25kPa)



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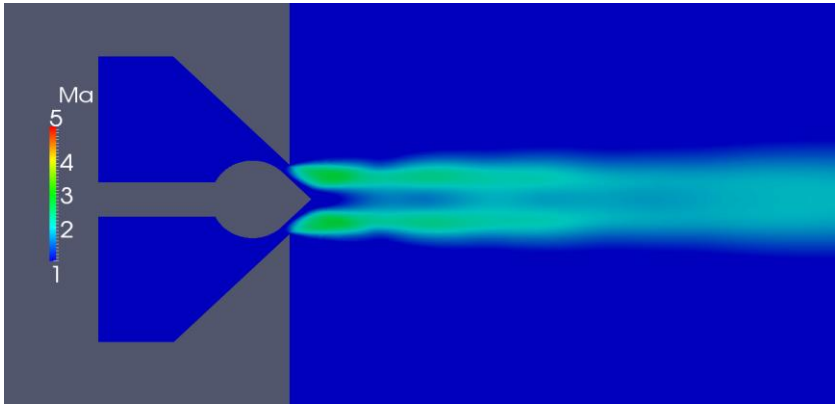
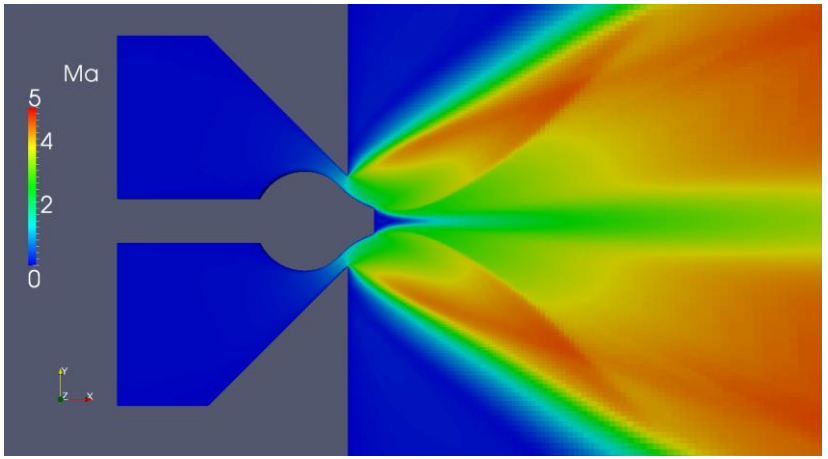


Geo Transformation

Re = 800 (250kPa)



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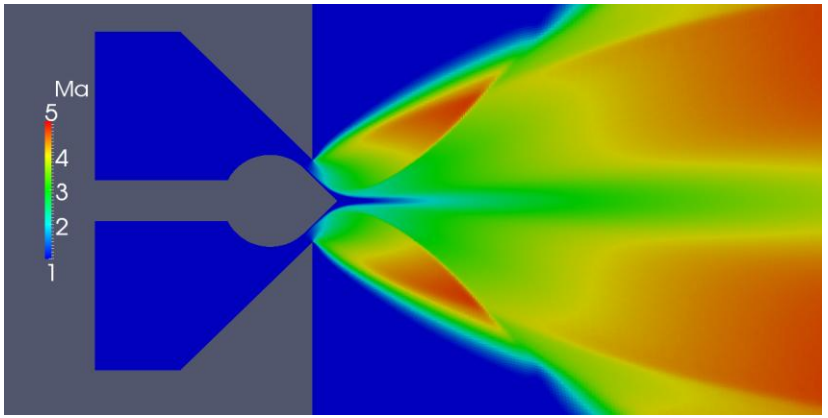
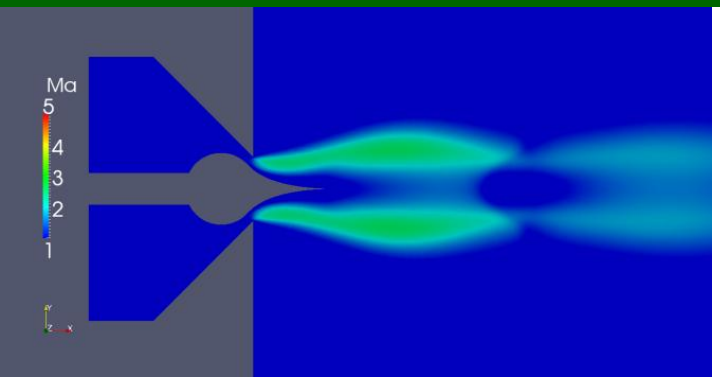
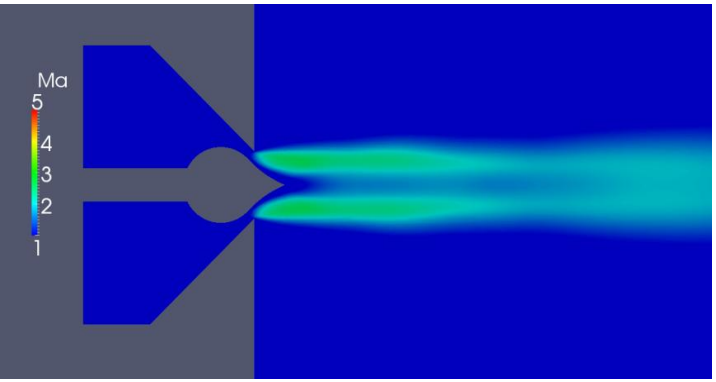


Geo Transformation

2D Geometric Study



25kPa Full Length MOC



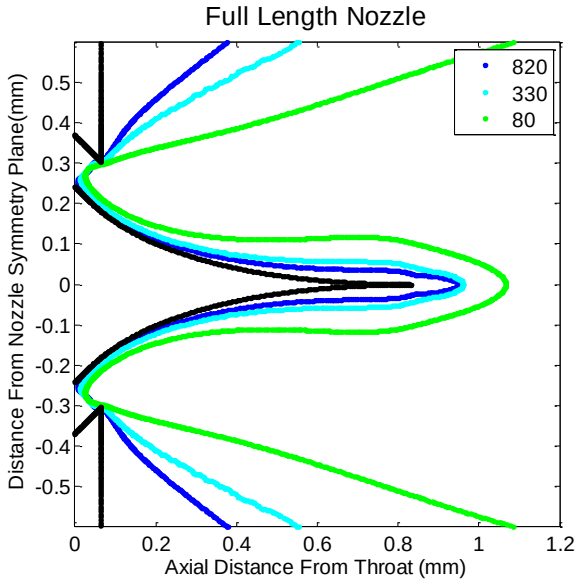
25kPa 40% Reduced Length

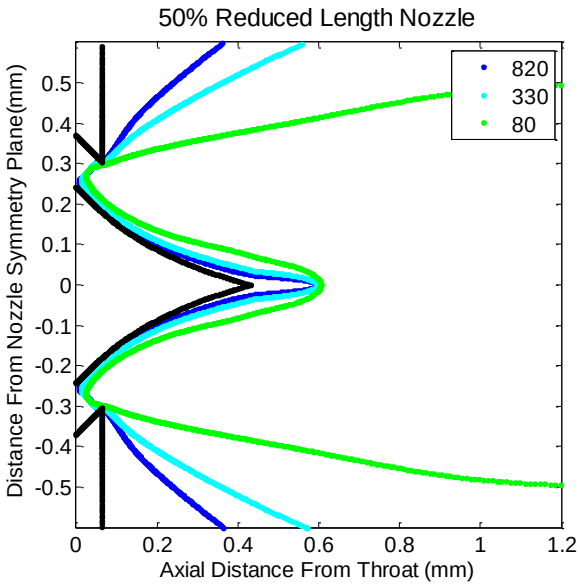
Reduced length Plug nozzles **reduce subsonic boundary** layer growth

→

and yield **superior flow alignment** and mild plume shocks at low Reynolds numbers

←





Reduced length nozzles (via truncation and geometric transformation) have a smaller surface area reducing viscous losses

At low Re, **viscous forces dominate favoring a shorter nozzle**

2D Geometric Study

Truncated Geometries

Re	FL	70T	60T	50T	40T	27T	20T
800	131.4	132.2	132.4	**132.6**	**132.6**	132.4	131.8
640	130.8	131.4	131.7	**131.9**	**131.9**	131.7	131.2
480	129.1	130.1	130.4	130.7	**130.8**	130.7	130.2
320	126.1	127.4	127.9	128.3	**128.6**	**128.6**	128.3
160	117.4	119.6	120.4	121.2	121.9	**122.4**	**122.4**
80	100.6	103.7	104.9	106.3	107.6	109.0	**109.8**

Geometric Transformations

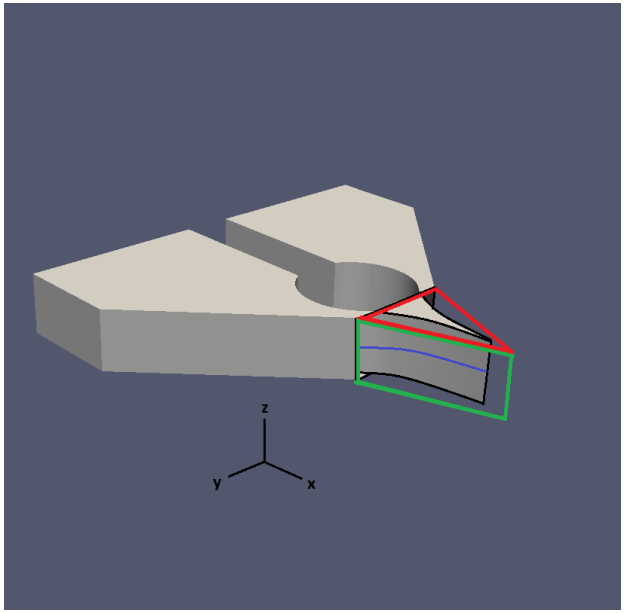
Re	FL	70RL	60RL	50RL	40RL	27RL
800	131.4	132.1	**133.0**	132.6	131.9	130.8
640	130.8	131.8	132.2	**132.4**	132.0	130.8
480	129.1	130.5	131.0	**131.3**	131.1	130.0
320	126.1	128.0	128.7	**129.2**	**129.2**	128.3
160	117.4	120.4	121.5	122.7	**123.2**	122.9
80	100.6	104.7	106.6	108.5	110.0	**110.4**

Comparison to other Geometries

Re	Sonic	30 Linear	Plug 40RL
800	111.8	**134.4**	131.9
640	111.4	**133.3**	132.0
480	110.7	**131.6**	131.1
320	110.4	128.2	**129.2**
160	109.6	118.8	**123.2**
80	106.0	101.7	**110.0**

- In general, nozzle geometries via geometric transformation (RL) outperform truncated (T) nozzles of a similar length.
- Best geometry is a function of the throat Reynolds number (Re)
- Lower Re favors shorter nozzles
- The variation in performance between different geometries scales inversely with Re
- 2D results indicate plug nozzles **good choice for low Re**

3D Performance Study



2D simulation does not account for:

- **Wall interactions with “cover plates”**
- **Expansion in the 3rd dimension**

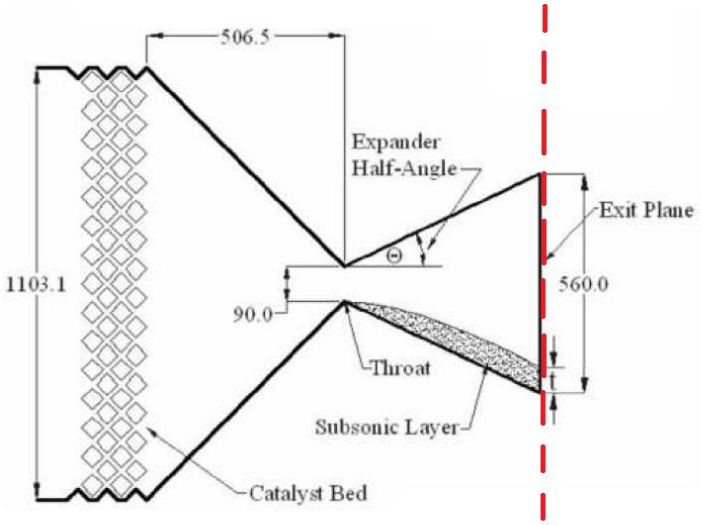
Results in a ***fundamentally different flow structure***

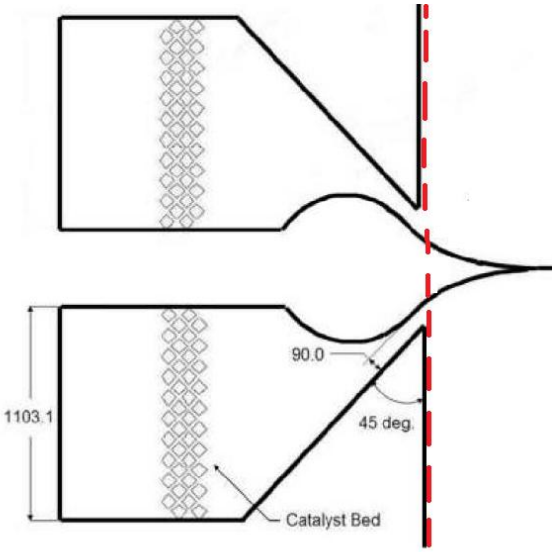
3D Parametric Design Variables:
Nozzles depth, Reynolds Number, and Geometry

Geometries:
30˚ linear-walled, 80% truncated plug

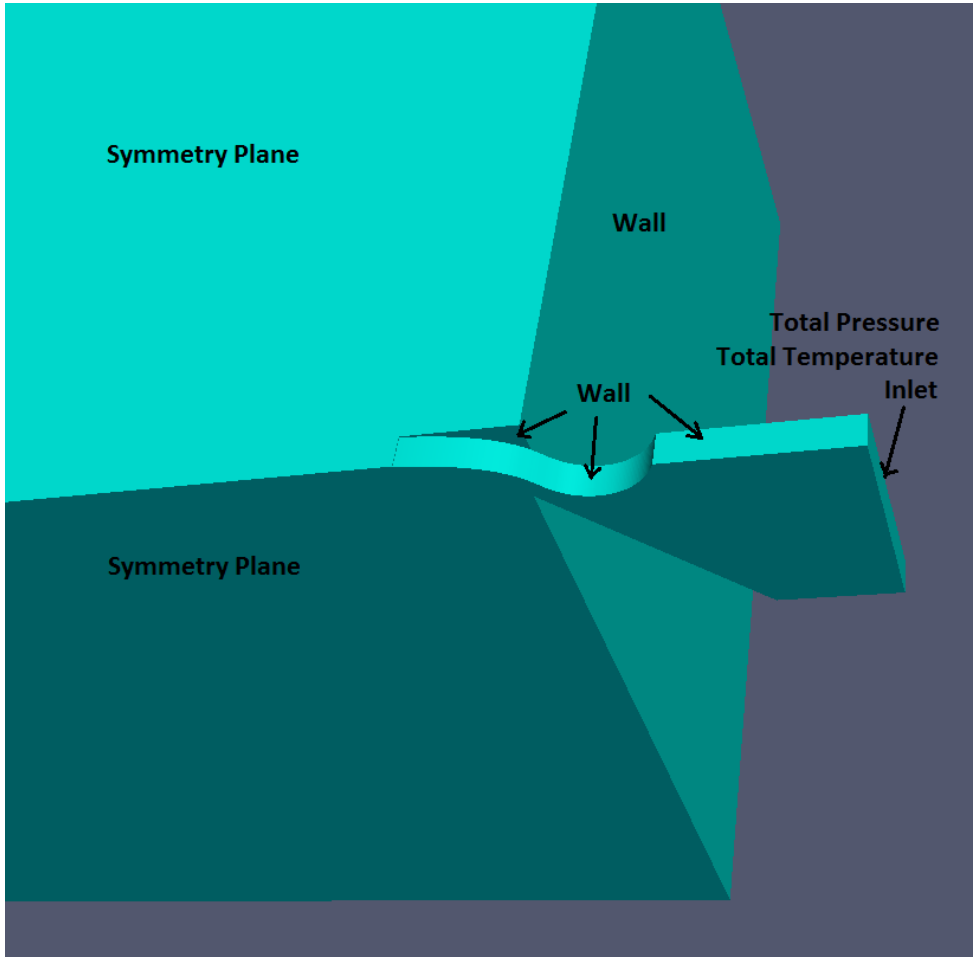
Nozzle Depths:
90, 180, 270, 360, and 450μm

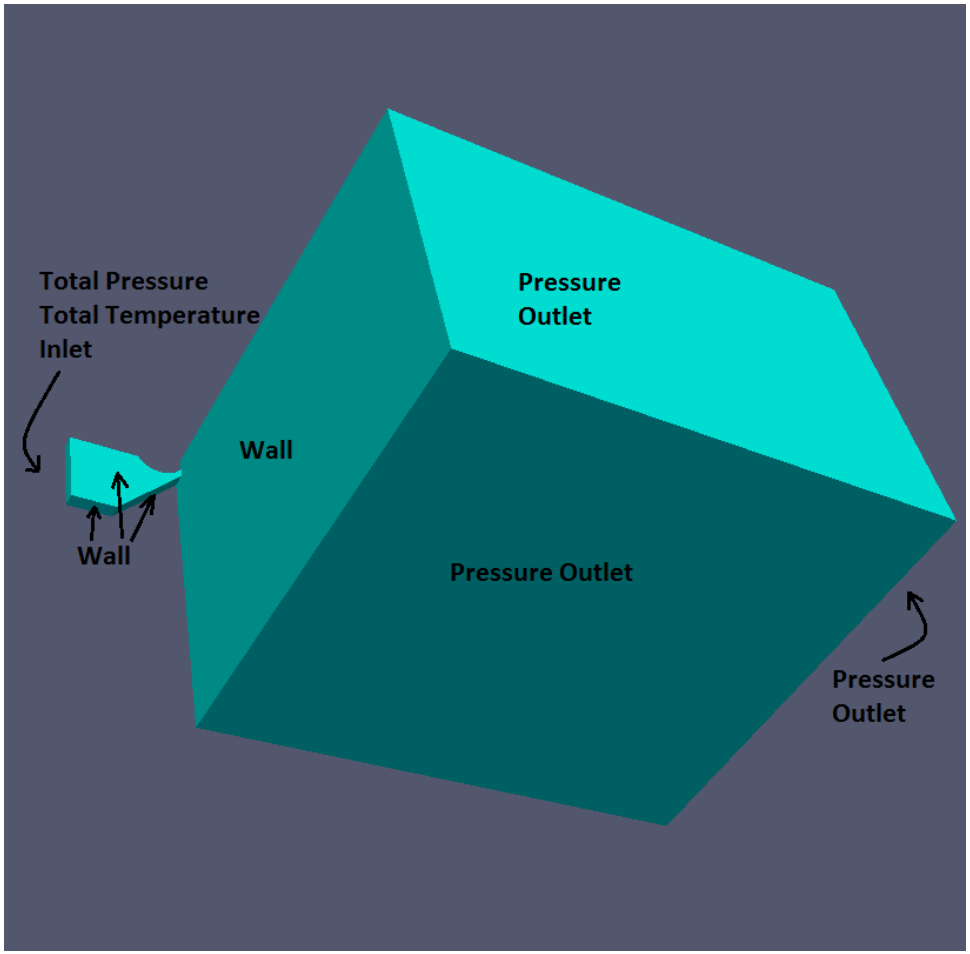
Throat Reynolds Numbers:
80, 160, 320, 480, 640, and 800



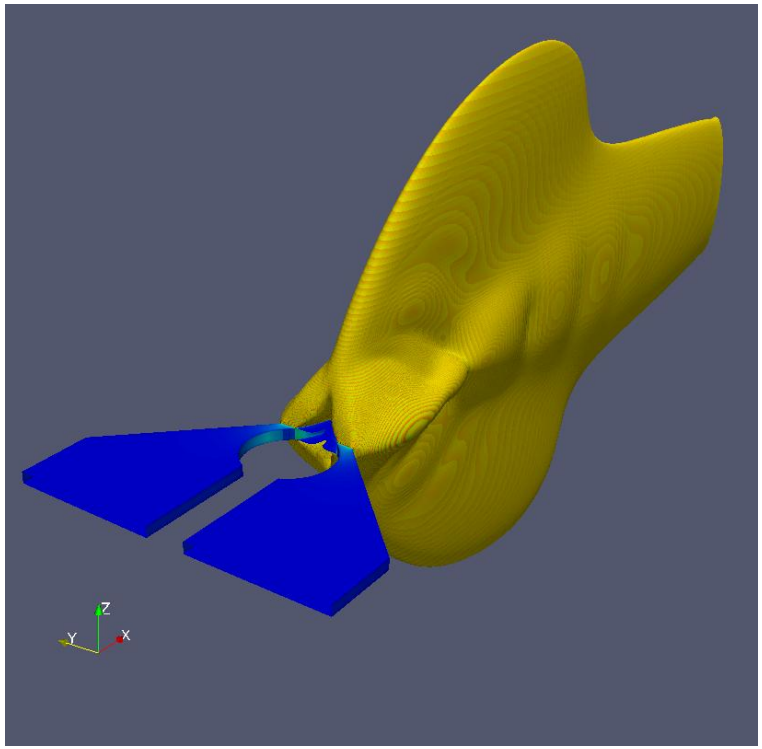


Computational Domain

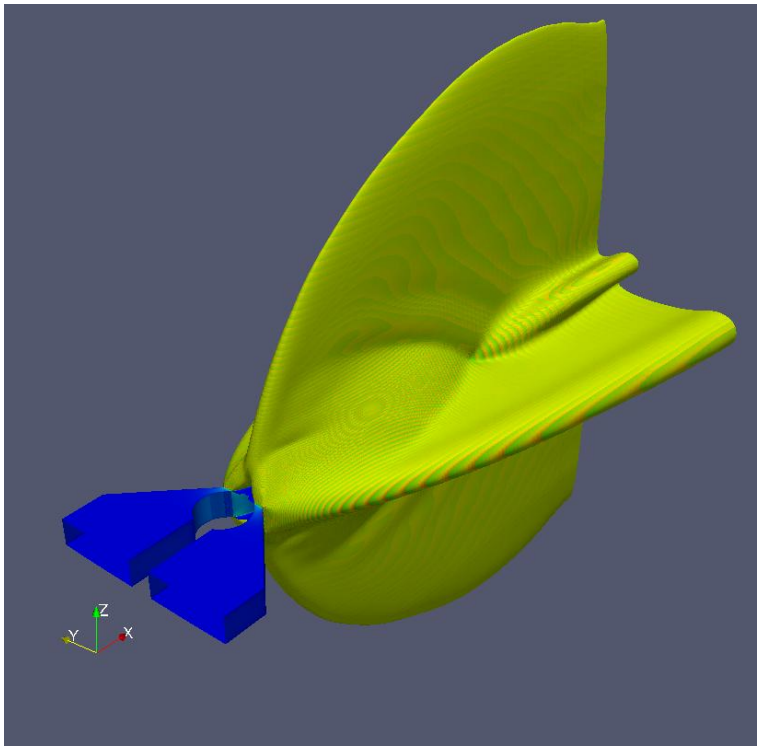




3D Flow Structure: Re = 800

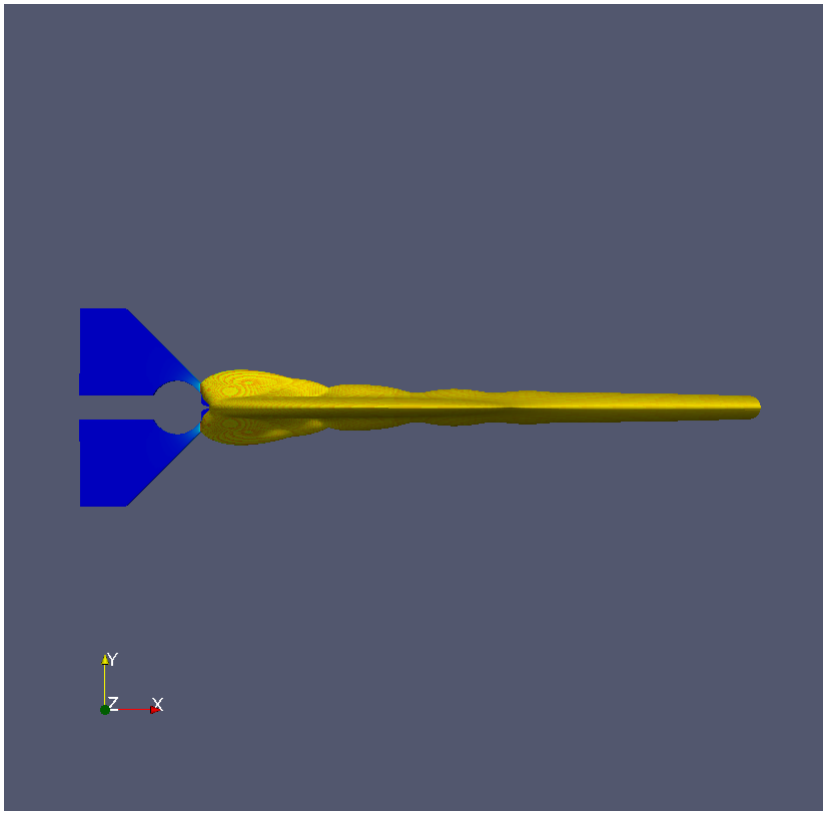


Depth = 90μm

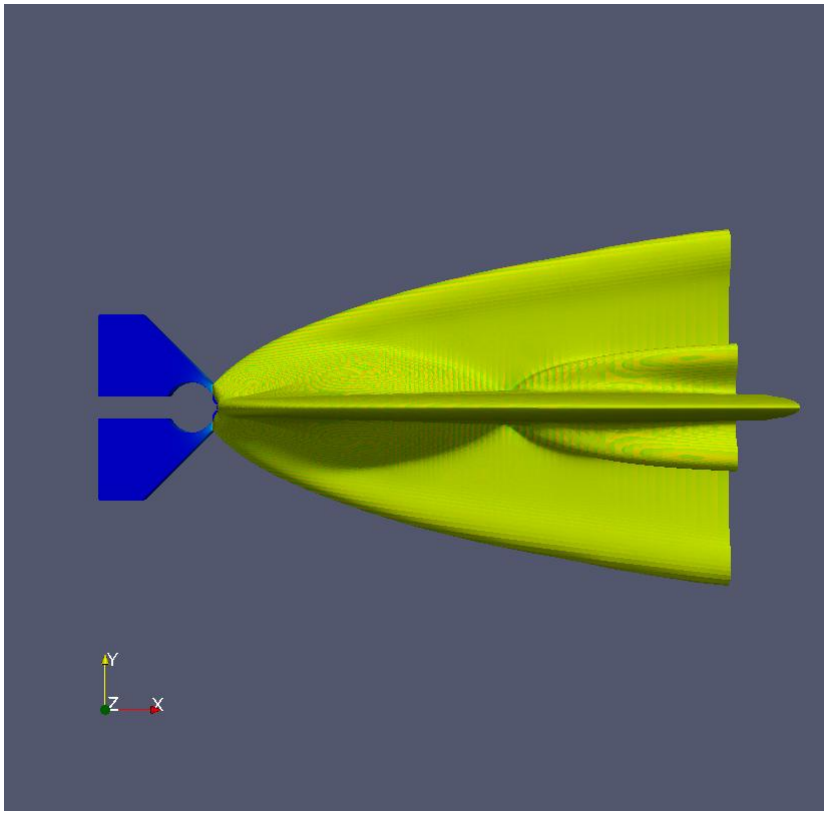


Depth = 360μm

3D Flow Structure: Re = 800



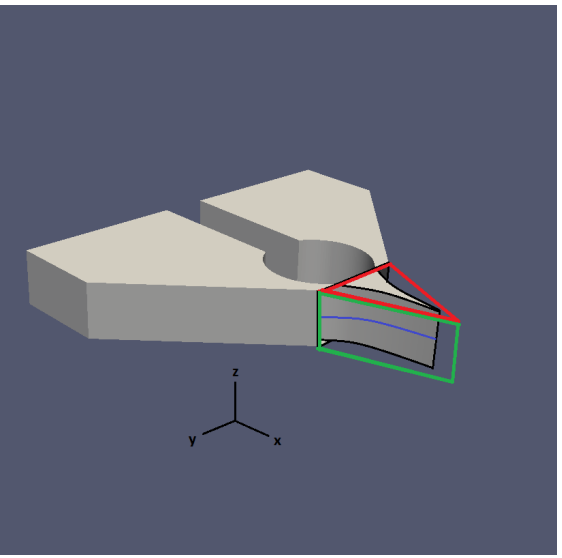
Depth = 90μm

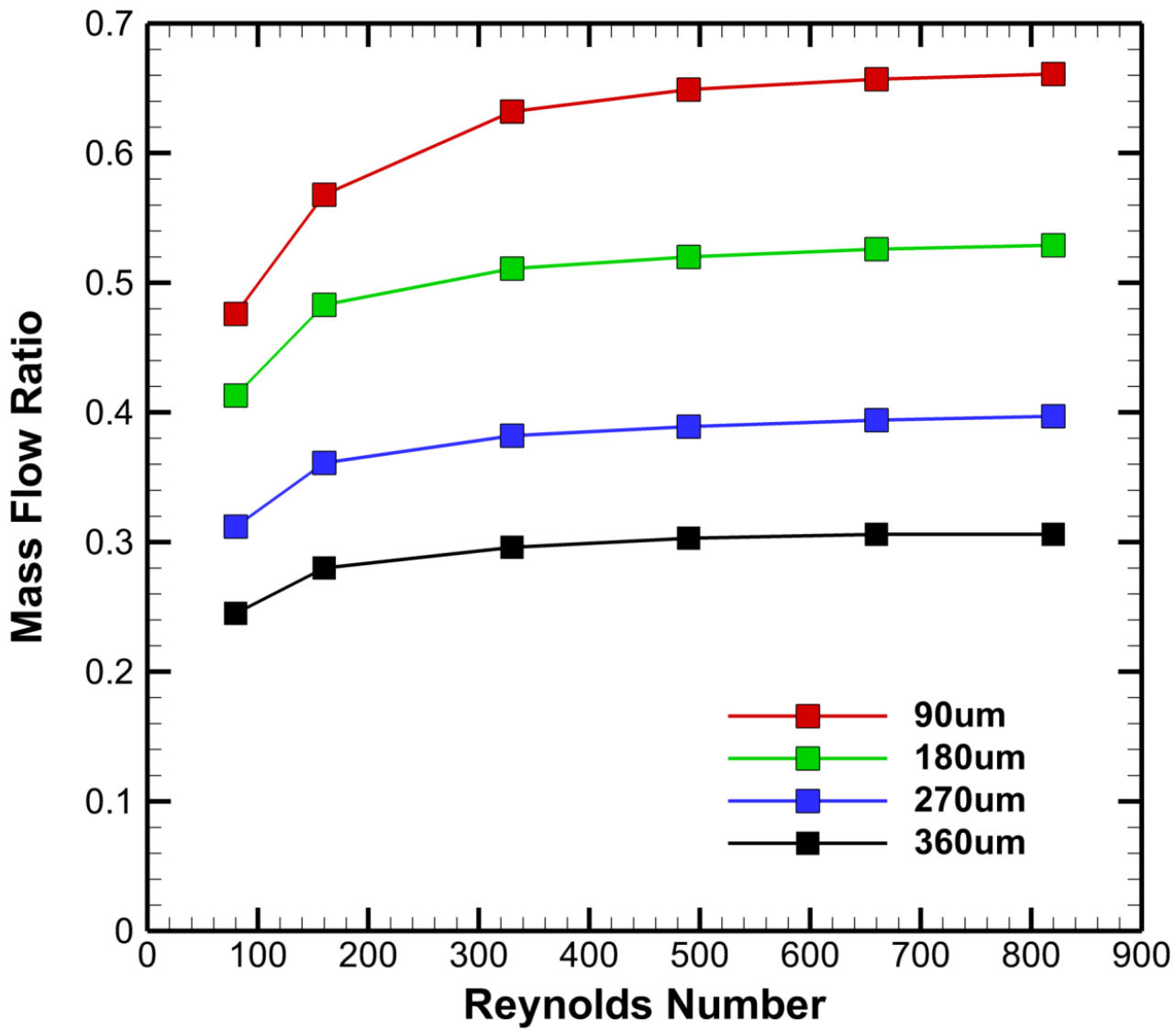


Depth = 360μm

Transverse Mass Flow Ratio (TMFR)

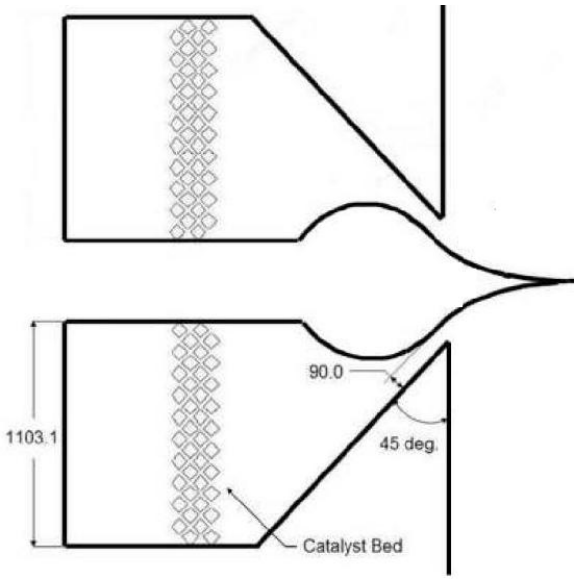
$$\text{TMFR} = \frac{\dot{m}_z}{\dot{m}_x + \dot{m}_y + \dot{m}_z}$$

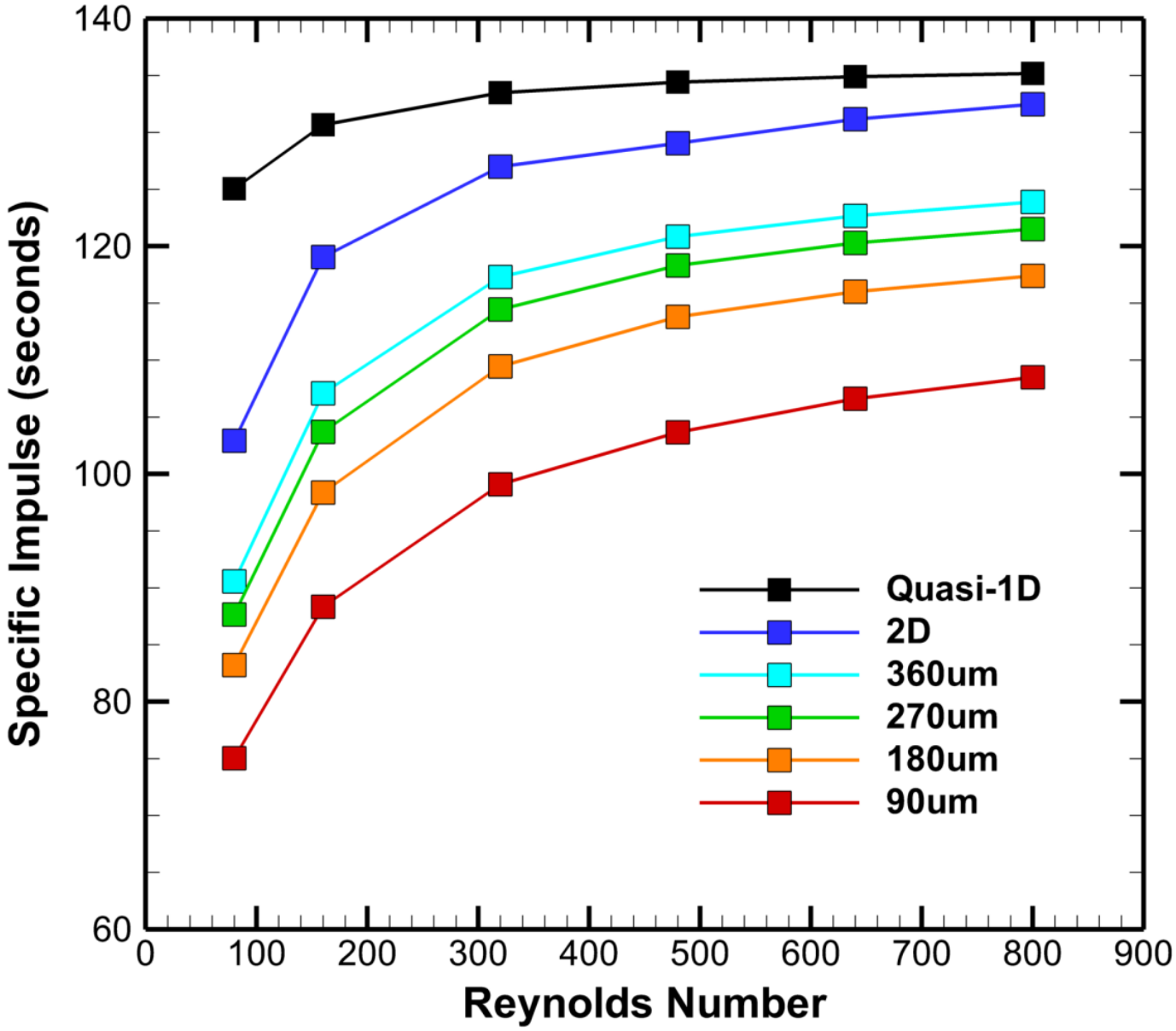




3D Plug Nozzle Performance

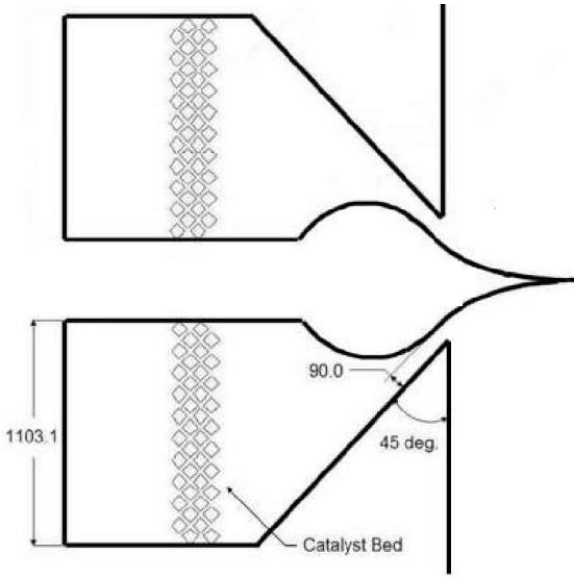
$$I_{sp} = \frac{F}{\dot{m}g}$$

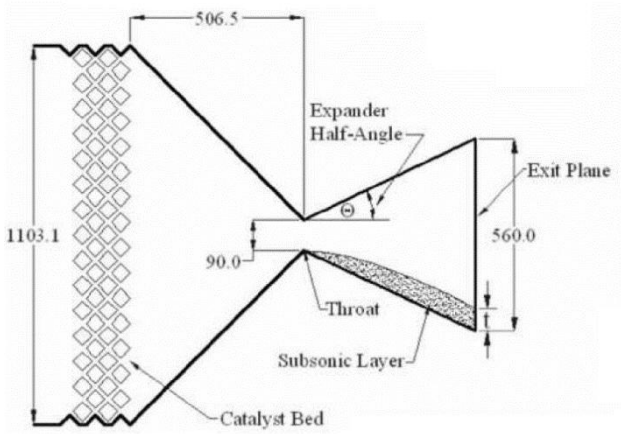


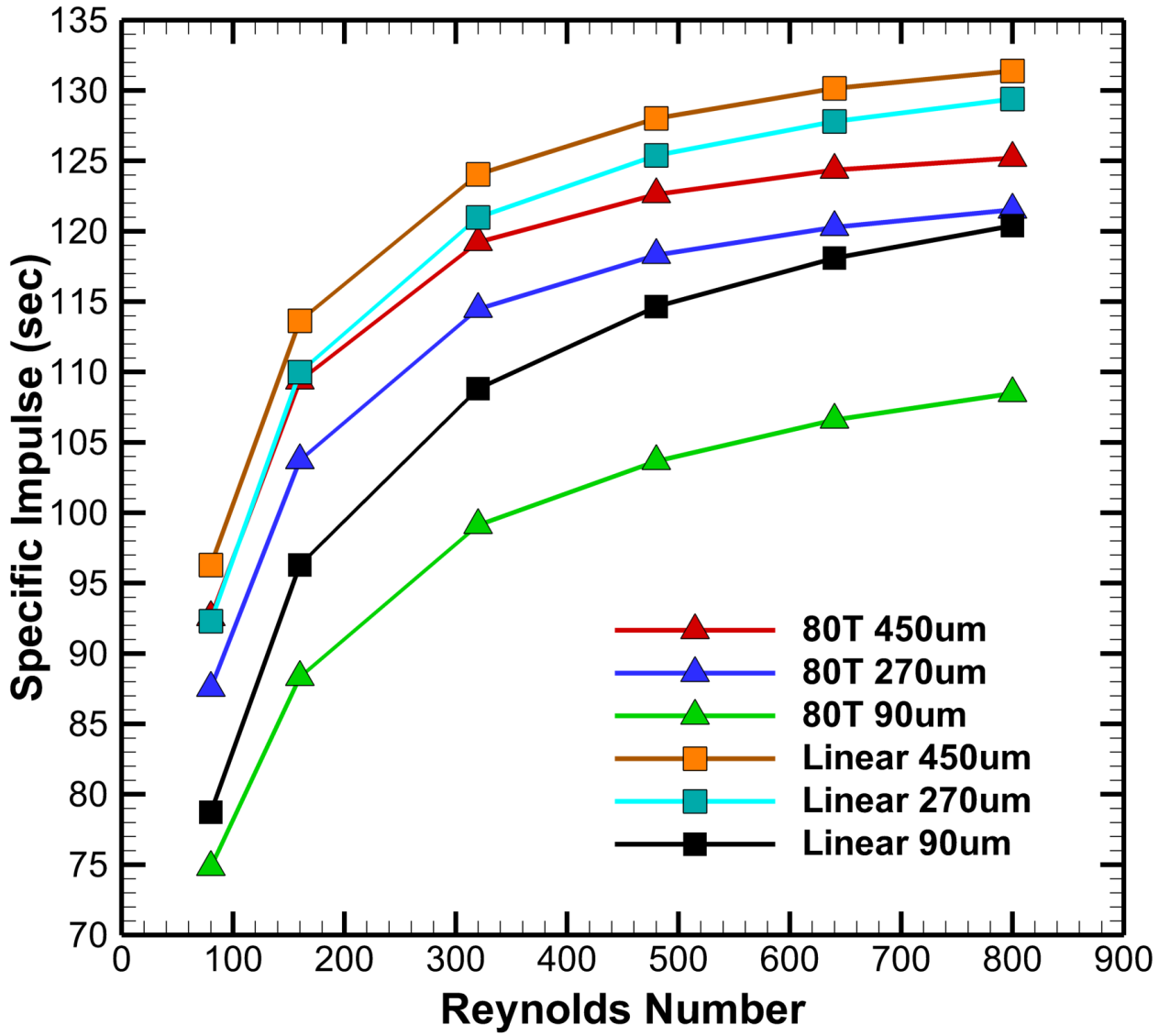


Linear-Walled vs 80% Truncated Plug

$$I_{sp} = \frac{F}{\dot{m}g}$$







Conclusions

- **Macroscale plug nozzle design methods (MOC) perform poorly on the microscale.**

- **Stress tensor effects should be included in the thrust equation for micronozzles (especially Re<100)**

- **Primary loss mechanism for planar plug micronozzles is geometric in nature caused by unbound etch direction expansion of the plume around the nozzle plug.**

  - magnitude is inversely proportional to depth and Re

- **Truncated plug nozzles (60% - 8%) show potential for performance enhancements and need further examination.**

Governing Equations

Continuity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0$$

Momentum Equation

$$\frac{\partial (\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U}\mathbf{U}) = -\nabla p + \nabla \cdot \tau$$

Energy Equation

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot \left(\mathbf{U}(\rho E + p)\right) = \nabla \cdot \left(k \nabla T + (\tau \cdot \mathbf{U})\right)$$

Ideal Gas Law

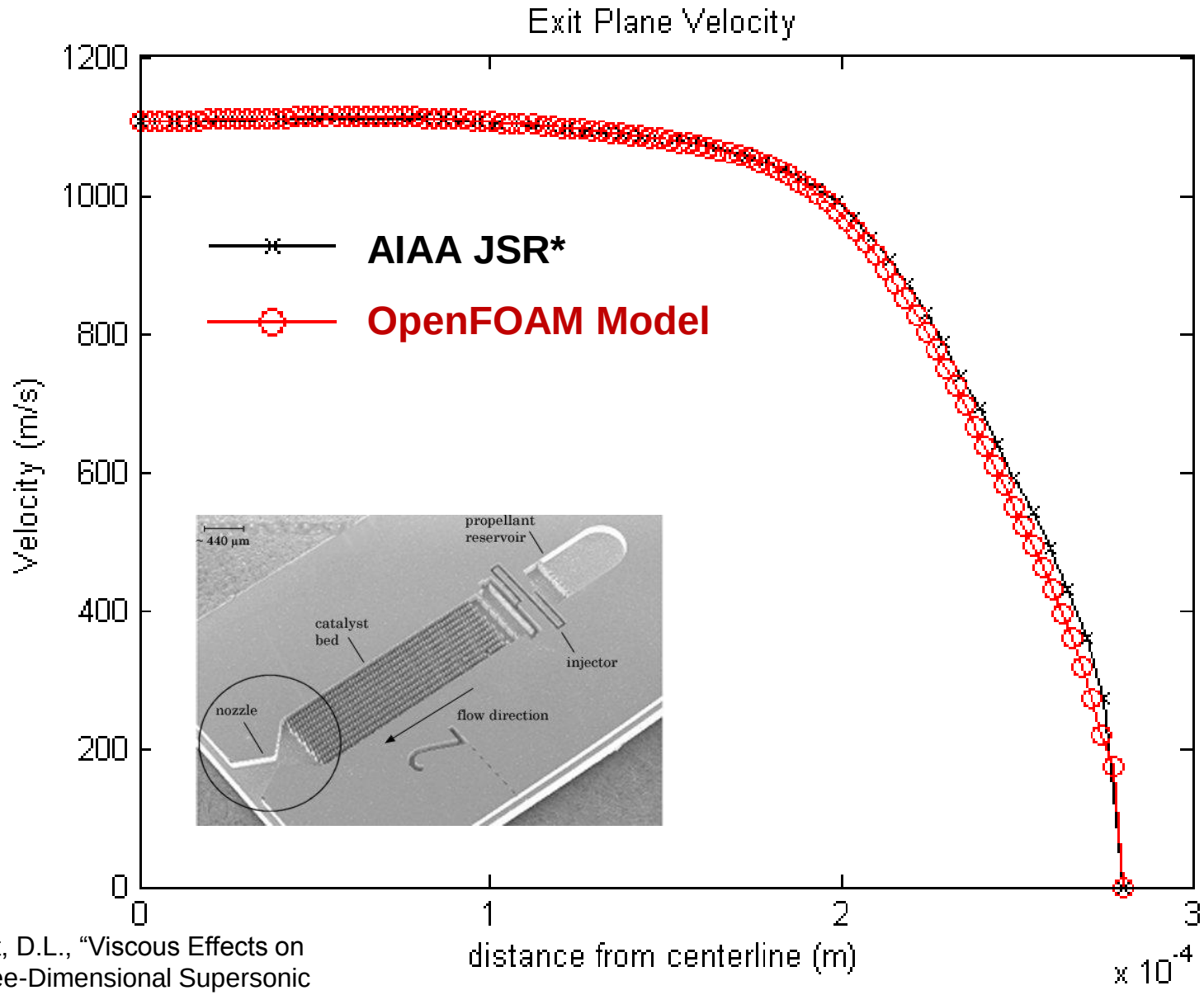
$$p = \rho R T$$

$$E = h - \frac{p}{\rho} + \frac{U^2}{2}$$

$$\tau = \mu \left((\nabla \mathbf{U} + \nabla \mathbf{U}^T) - \frac{2}{3} \nabla \cdot \mathbf{U} \right)$$

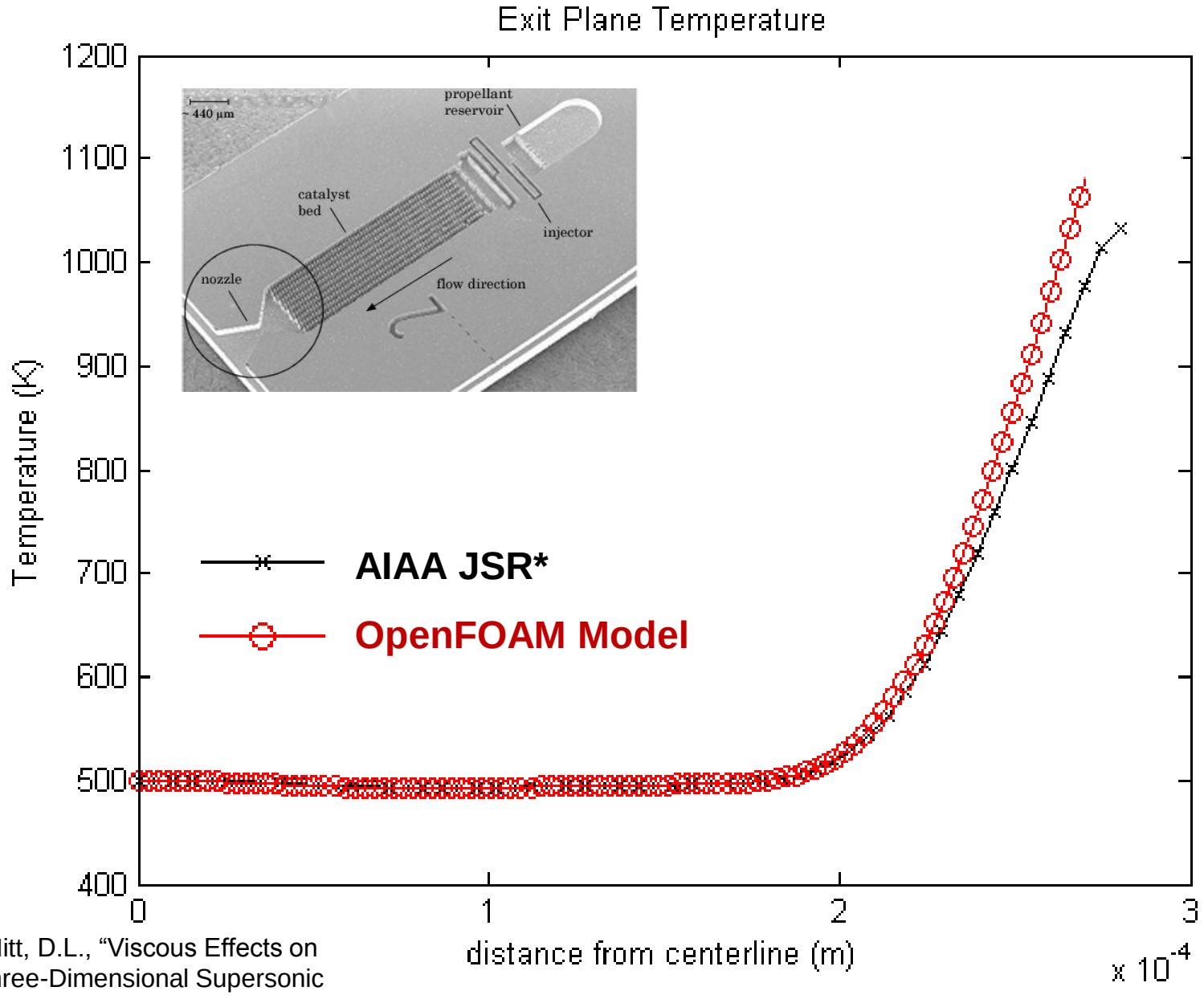
t	time
p	pressure
T	temperature
ρ	density
U	velocity
R	gas constant
μ	kinematic viscosity
k	thermal conductivity
τ	wall shear stress

Model Validation: Velocity



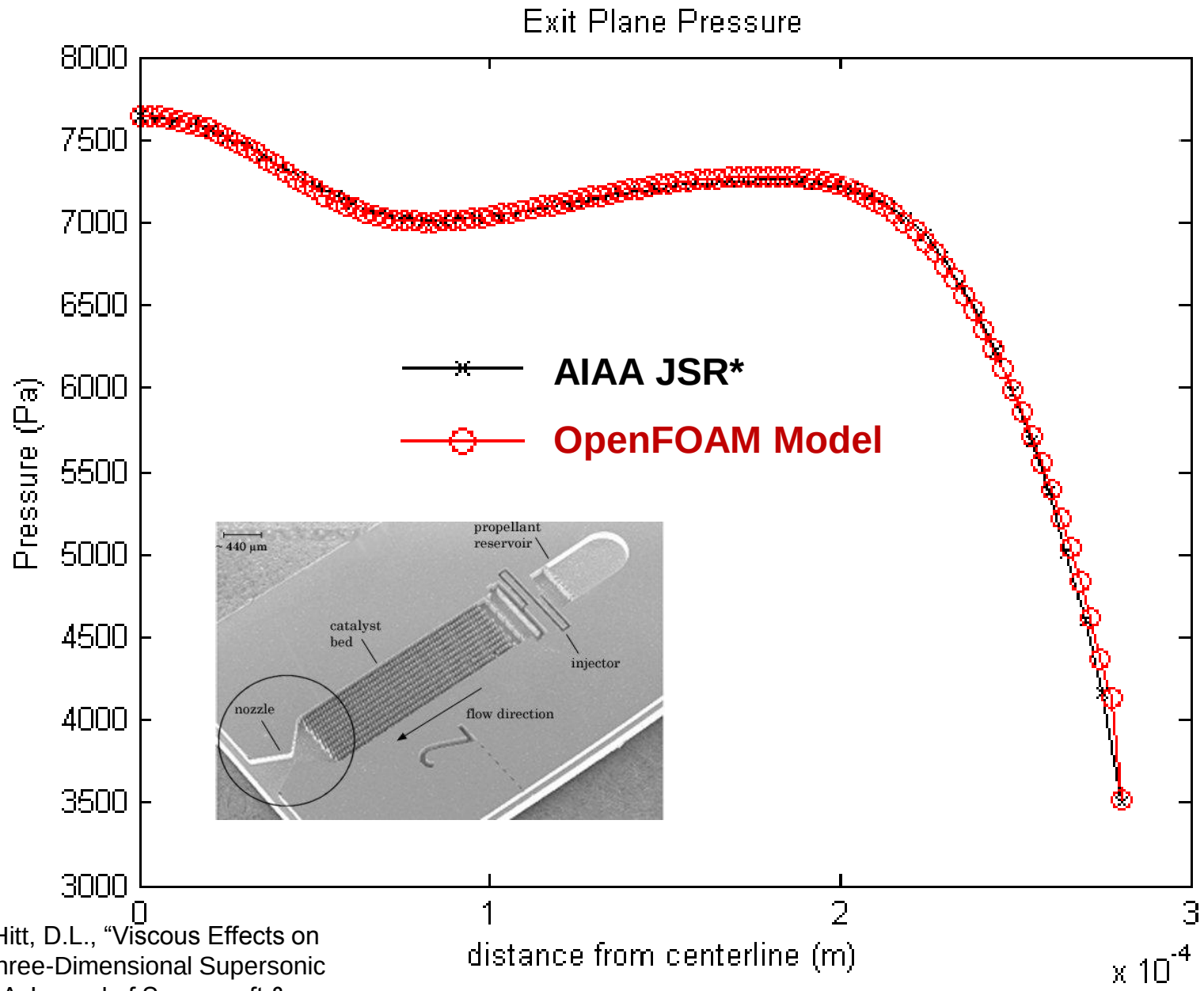
*Louisos, W.F. & Hitt, D.L., "Viscous Effects on Performance of Three-Dimensional Supersonic Micronozzles" AIAA Journal of Spacecraft & Rockets, Vol. 45, No. 1, pp. 51-58, 2012

Model Validation: Temperature



*Louisos, W.F. & Hitt, D.L., "Viscous Effects on Performance of Three-Dimensional Supersonic Micronozzles" AIAA Journal of Spacecraft & Rockets, Vol. 45, No. 1, pp. 51-58, 2012

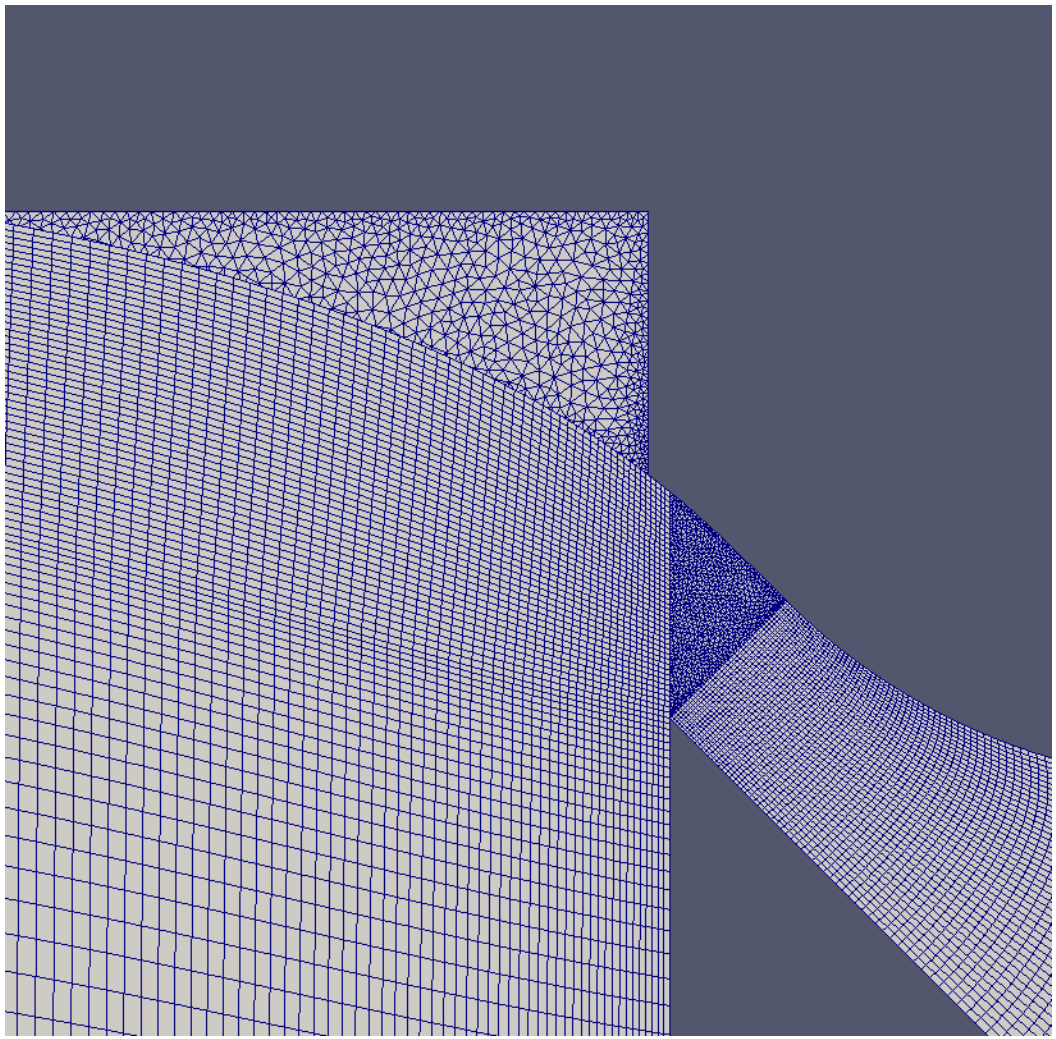
Model Validation: Pressure



*Louisos, W.F. & Hitt, D.L., "Viscous Effects on Performance of Three-Dimensional Supersonic Micronozzles" AIAA Journal of Spacecraft & Rockets, Vol. 45, No. 1, pp. 51-58, 2012

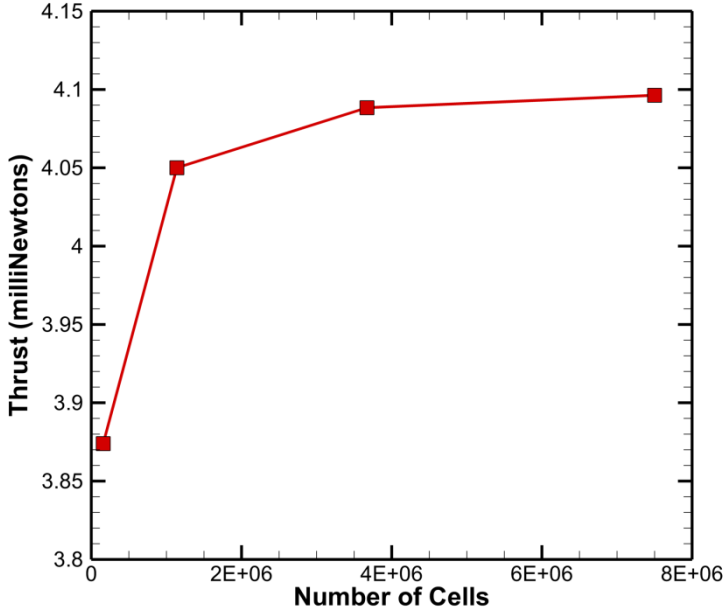
Computational Grid

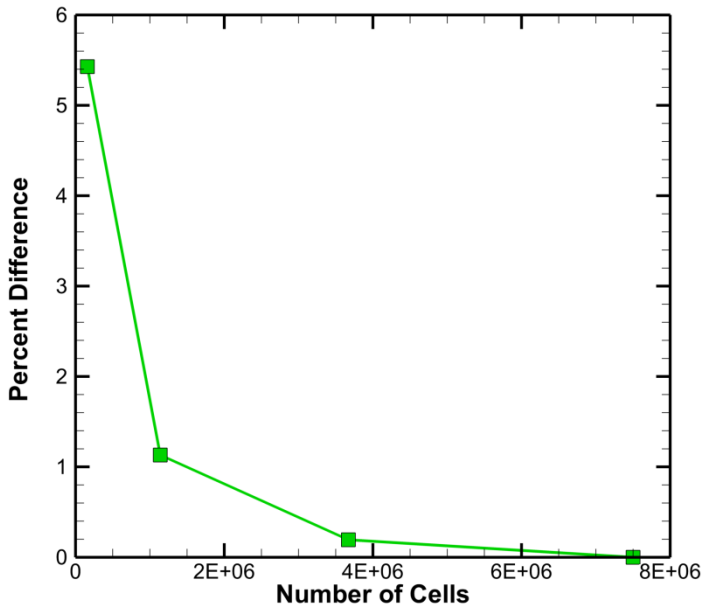
- **Pointwise Mesh Generation**
- **Combination of Structured and Unstructured Finite Volumes**
- **Mesh Smoothing**
  - Steger-Sorensen Boundary Control Function
  - Floating Boundary condition between blocks
- **Final Mesh 3 – 7 million nodes (Depth Dependent)**
  - Nozzle thrust and wall temperature used as stopping criteria for mesh refinement
  - Less than 1% change in simulated thrust output for final mesh
- **Symmetry used to decrease computational cost**



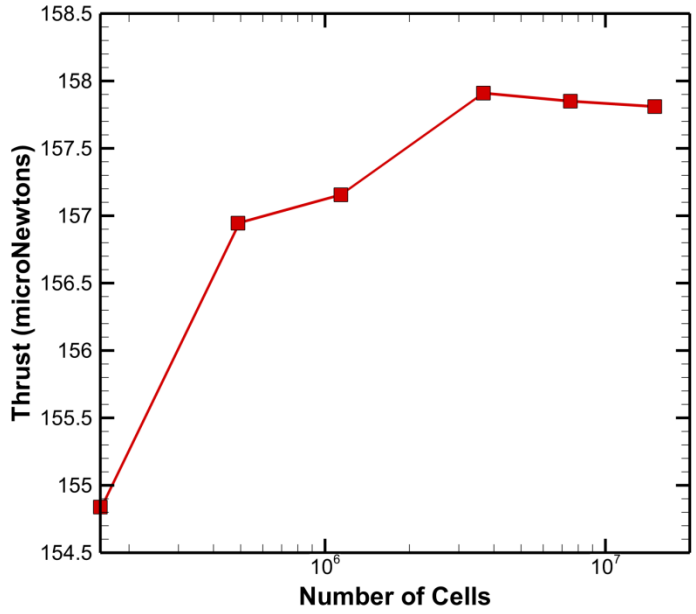
Grid Sensitivity Study

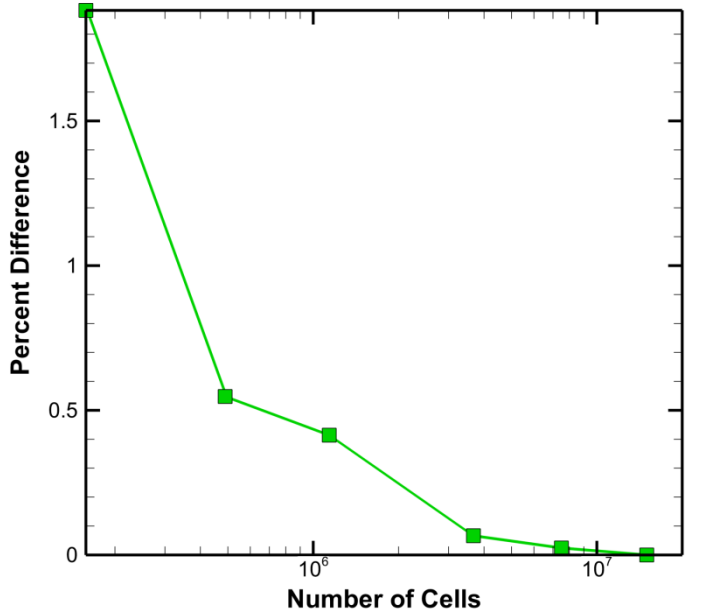
Re = 800





Re = 100





Linear Walled Nozzles

- Geometric studies examining expander angle's effect on micronozzle performance (Bayt 1998, Ketsdever 2004, Louisos 2008)
- Numerical study examining expander angle's effect on 3D micronozzle performance - (Alexeenko 2002, Louisos 2009)
- Analysis of Condensation effects in linear micronozzles - (Louisos 2012)
- Heat transfer and wall temperature effect on micronozzle performance - (Alexeenko 2005, Louisos 2007, Louisos 2012, Hameed 2012)

Plug Nozzles

- Numerical examination of plug truncation effects on 2D micronozzle performance – (Zilic, et al, 2007)
- Numerical study using Direct Simulation Monte Carlo (DSMC) to model center body axisymmetric micronozzle designs - (Stein, et al, 2011)

Plug micronozzles have been examined much less extensively

Acknowledgments

Thank you to the Vermont Space Grant Consortium (VSGC). Without their support, this research would not have been possible.

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Thank you.

Questions?