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# FUN3D and USM3D Results for Nozzle Configurations

4<sup>th</sup> AIAA Propulsion Aerodynamics Workshop  
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NASA Langley Research Center  
July 8, 2018

# Overview

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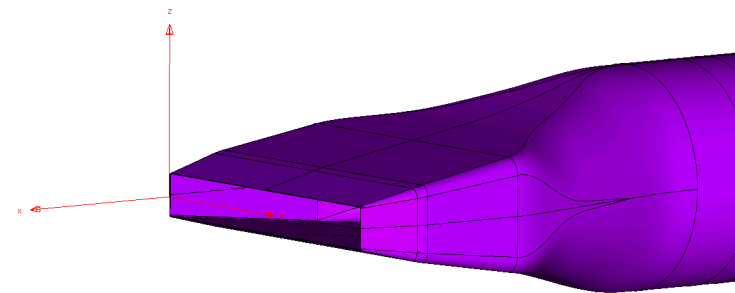


- Problem Statement
- CFD Codes Used
- Boundary Layer Modeling
- Grid Generation
- Problem Setup
- Results
- Summary

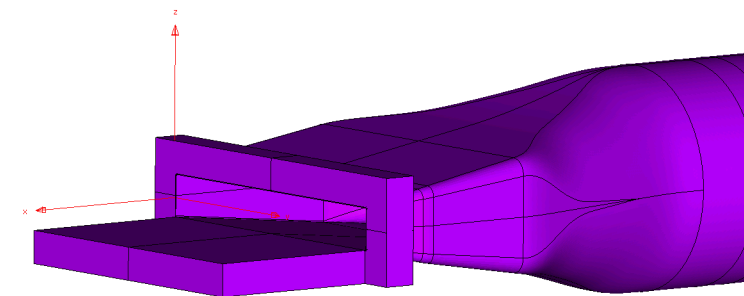
# Problem Statement



- Work performed for the fourth Propulsion Aerodynamics Workshop (PAW04)
- Two required nozzle geometries
- Perform grid convergence study for nozzle pressure ratio (NPR) of 3.5
- Select appropriate grid resolution to simulate NPRs of 1.89 and 2.45



Baseline Nozzle

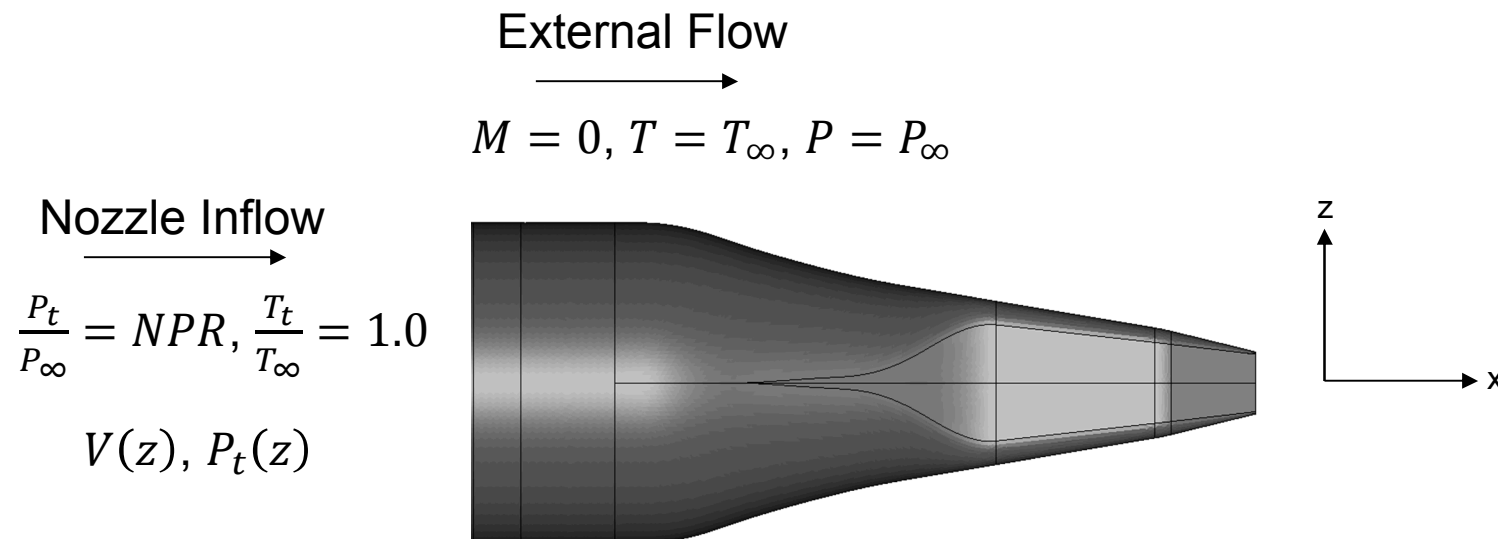


Nozzle w/ Aft Deck

# Boundary Conditions

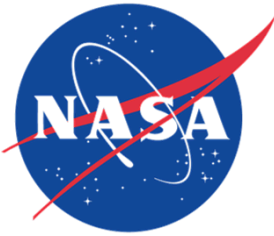


- Inflow boundary conditions
  - Total pressure set based on NPR
  - Total temperature set to ambient temperature
  - Boundary layer from upstream duct (profiles provided)
- External flow set to static ambient conditions



# Numerical Techniques

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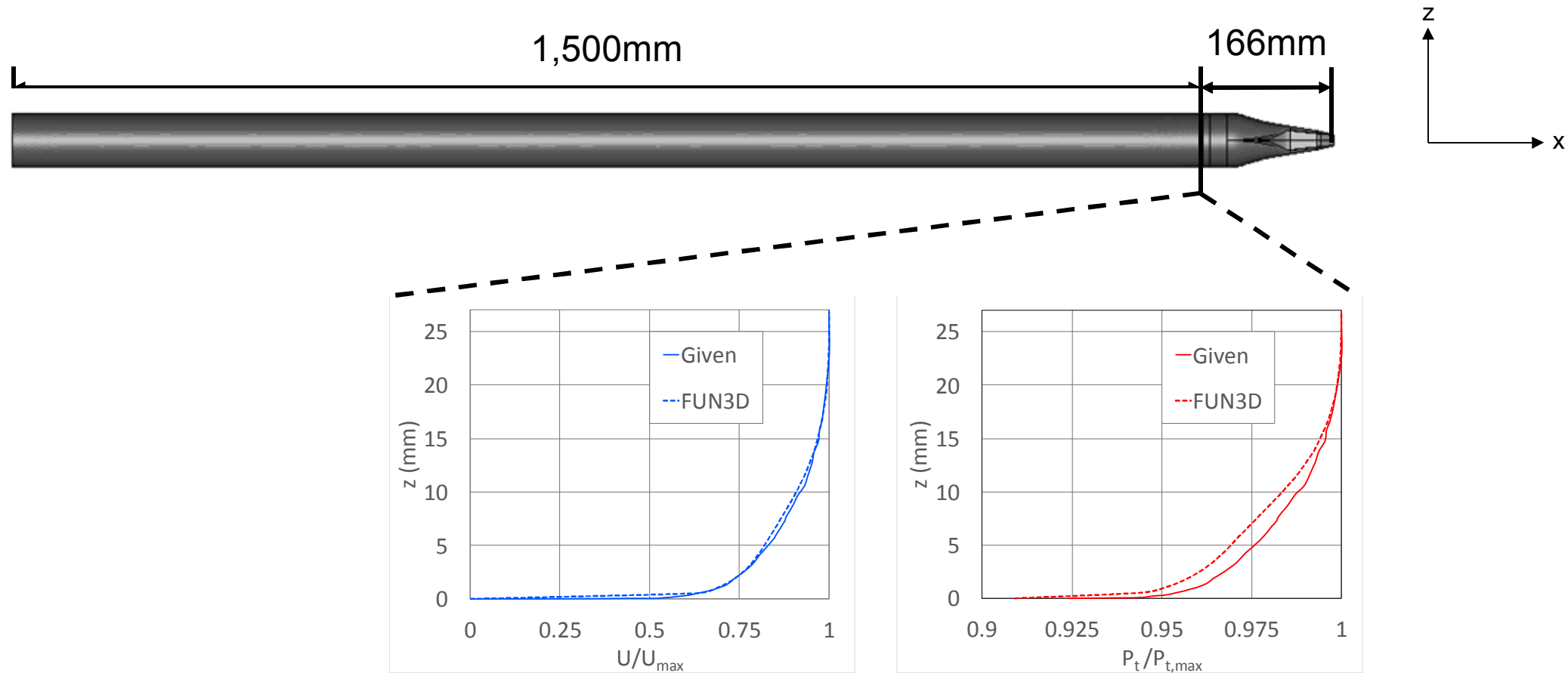


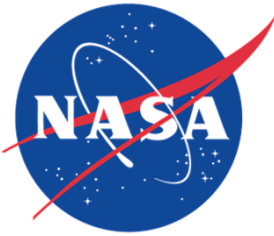
- FUN3D Flow Solver
  - Mixed Element Node-Based, Finite Volume
  - Navier-Stokes
  - Time Integration
    - » Steady
  - Upwind Spatial Discretization
    - » Roe flux-difference w/ min-mod flux limiter
  - Turbulence Model
    - » SA
- USM3D Flow Solver
  - Tetrahedral Cell-Centered, Finite Volume
  - Navier-Stokes
  - Time Integration
    - » Steady
  - Upwind Spatial Discretization
    - » Roe flux-difference w/ min-mod flux limiter
  - Turbulence Models
    - » SA

# Boundary Layer Modeling – FUN3D



- Allow BL to develop naturally by means of upstream duct
  - Eliminates need to specify distributions at inflow boundary





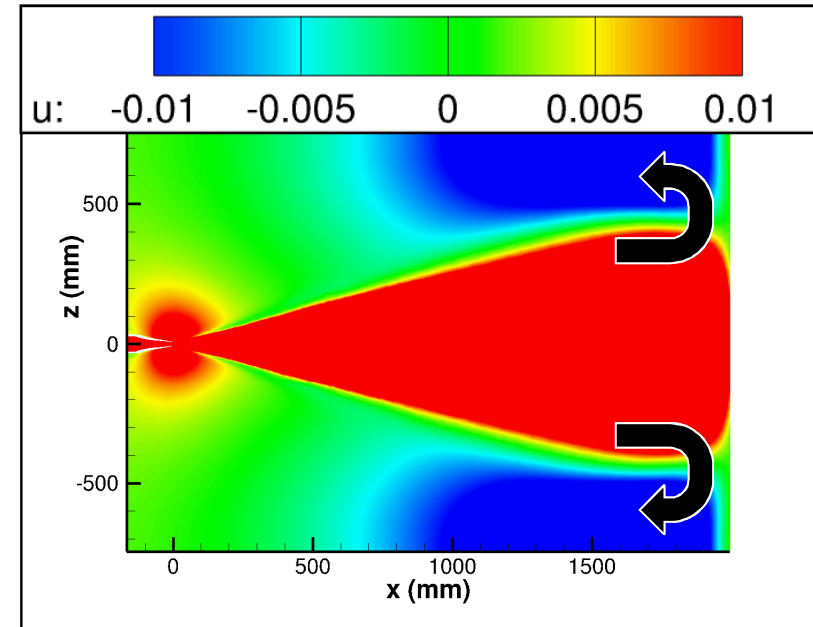
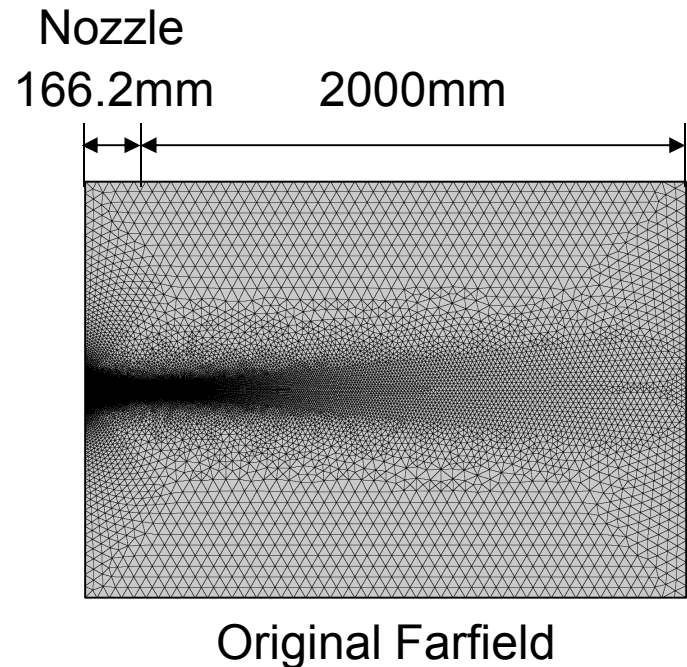
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# GRID GENERATION

# Farfield Boundary Issues – FUN3D

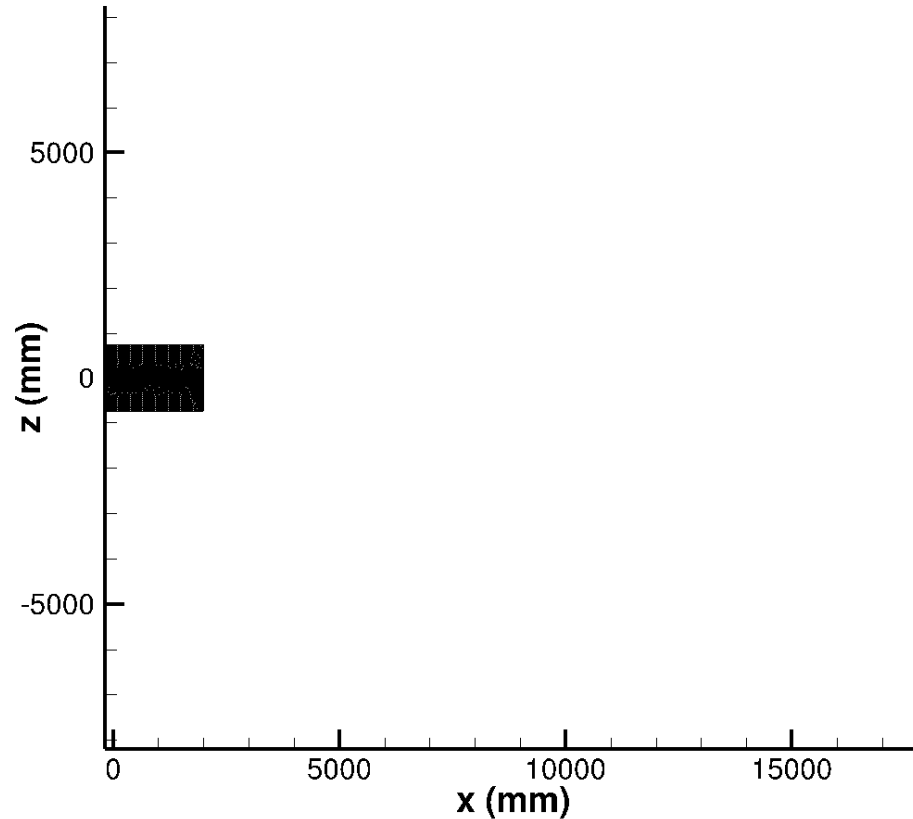


- Grids were created using Pointwise
- Goal was to replicate the size of the provided grids
- However, issues were encountered with the farfield

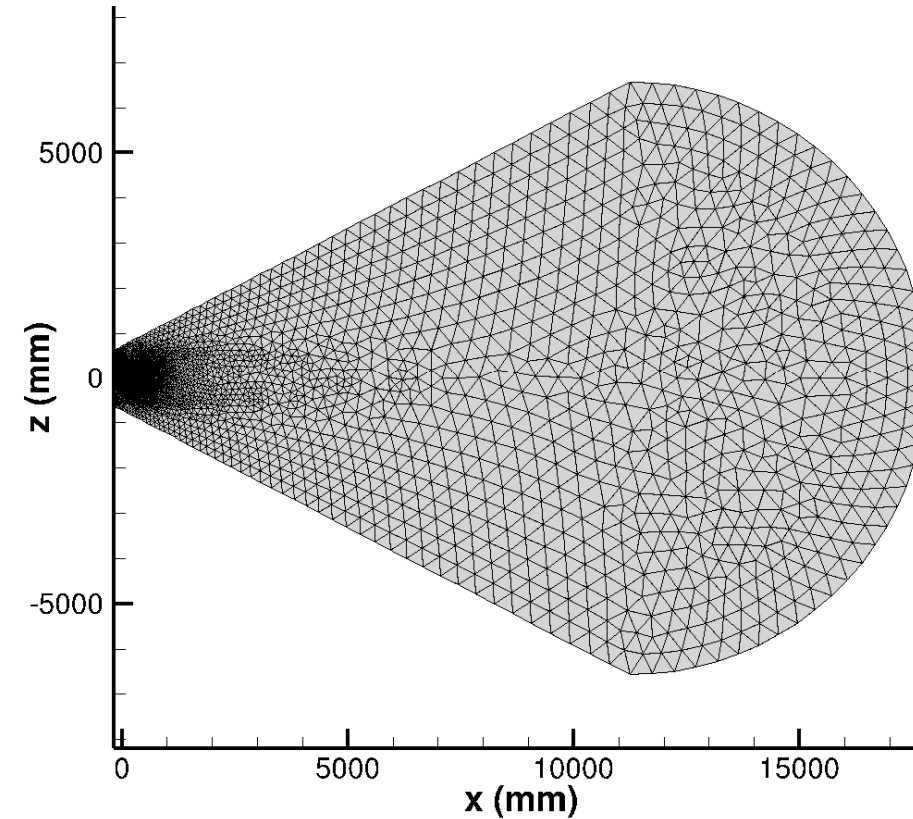


$M \sim 0$  at farfield  
boundary

# Grid Modifications – FUN3D



Provided Grid

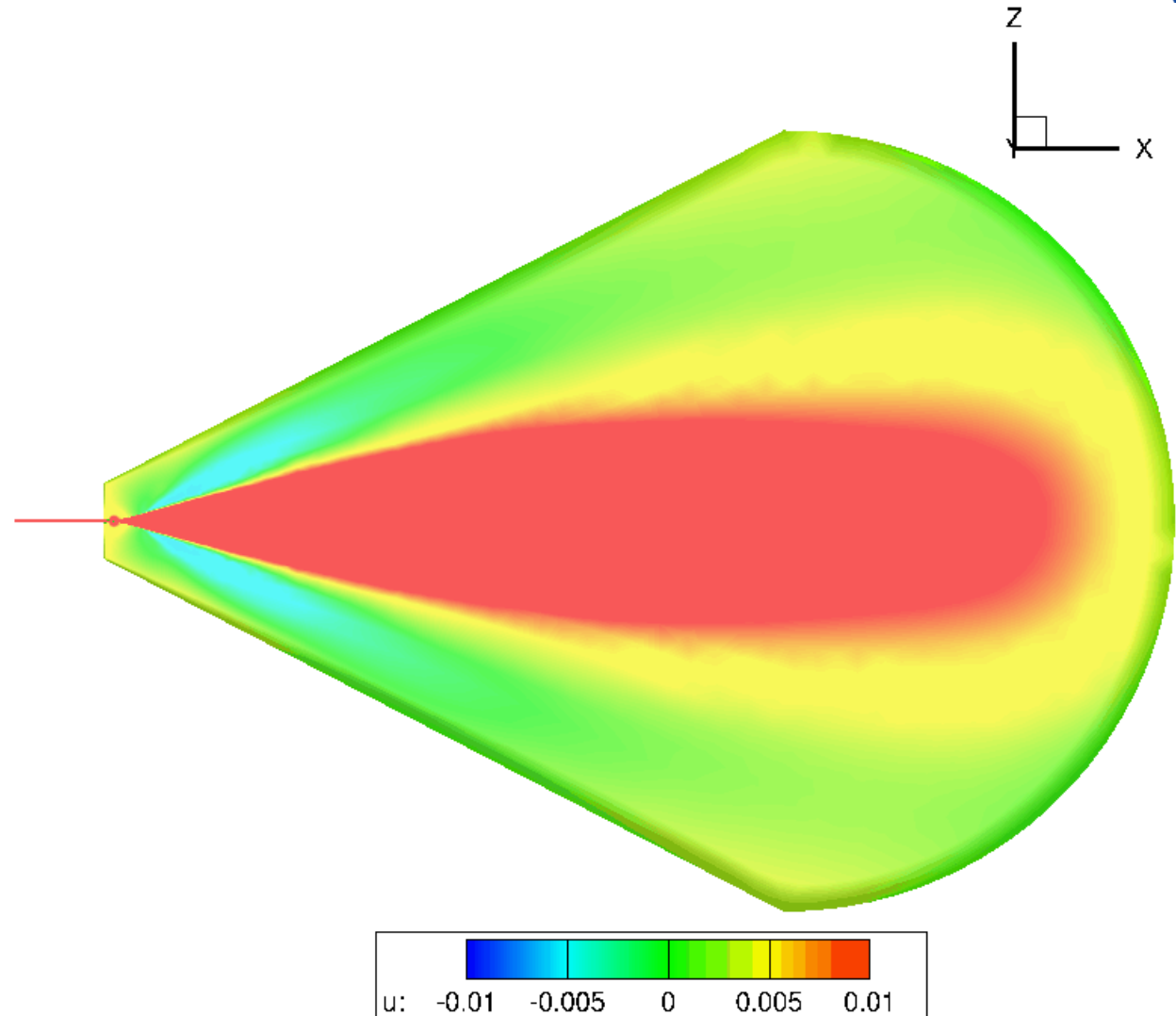


Modified Grid

# Modified Farfield Boundary – FUN3D



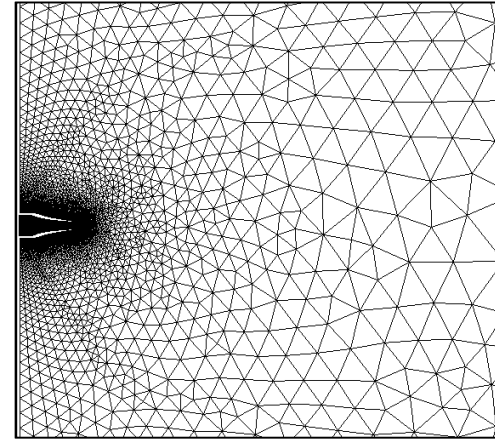
- No more wall behavior at farfield boundary
- Small regions of negative velocity caused by entrainment



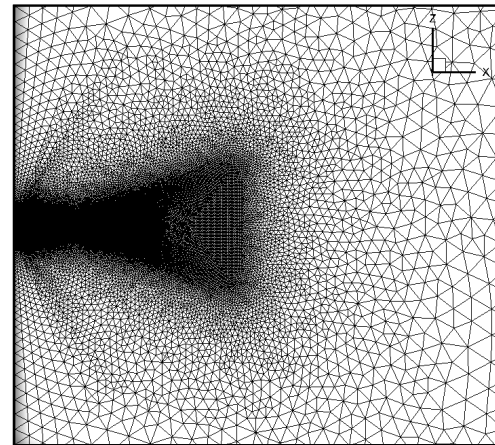
# Plume Resolution – FUN3D



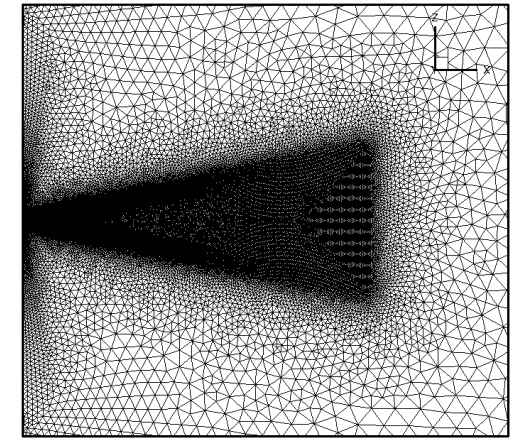
- Mach and pressure profiles requested at distances up to 250mm downstream
- Three different plume resolutions considered
  - No plume resolution
  - Resolution up to 450mm
  - Resolution up to 5,450mm



No plume

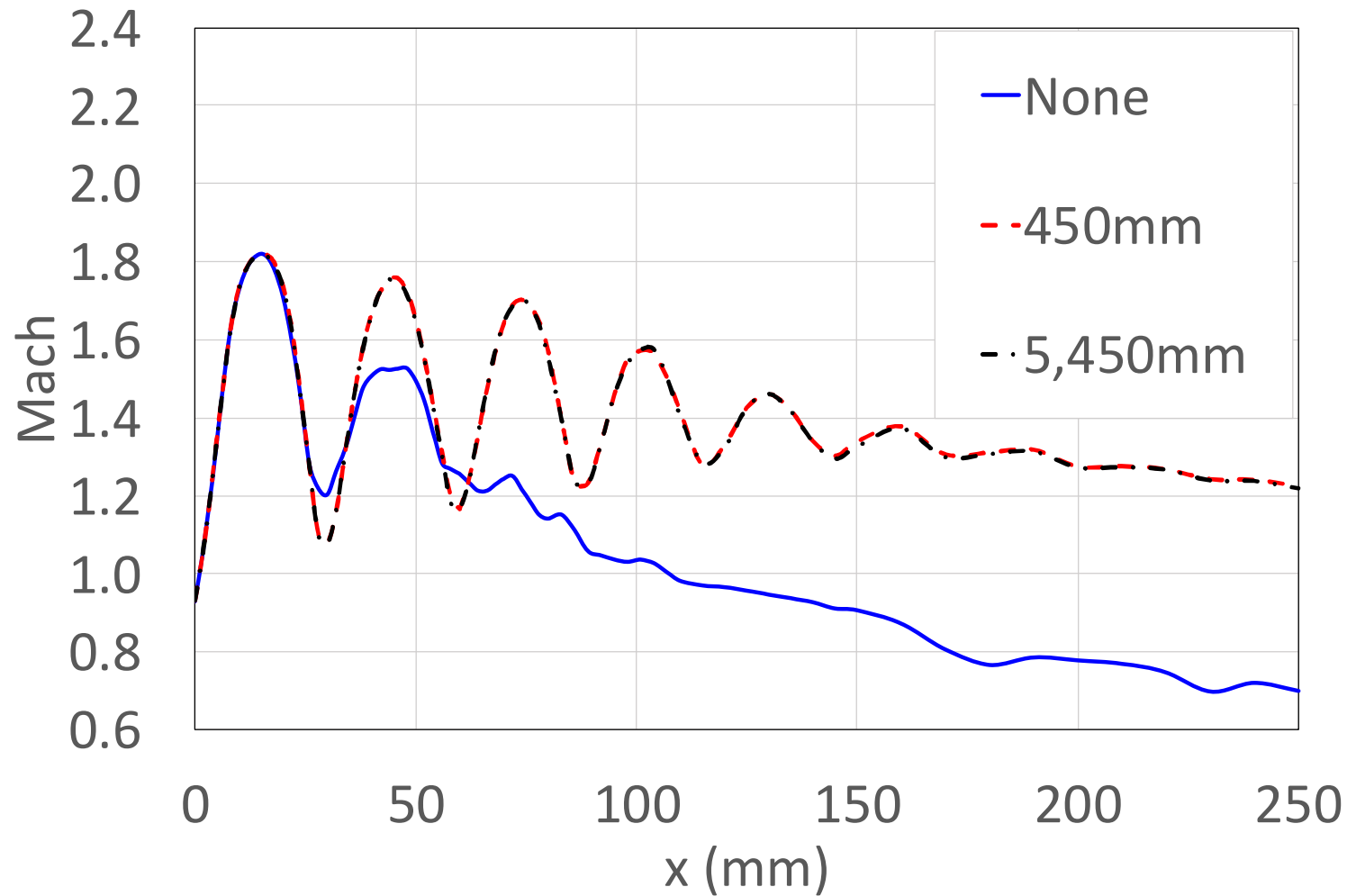


450mm plume



5,450mm plume

# Plume Resolution Study – FUN3D

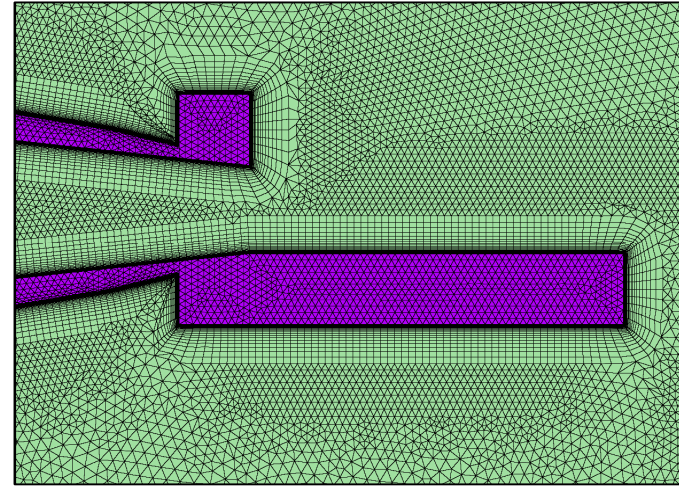


Plume resolution up to 450mm sufficient for this analysis

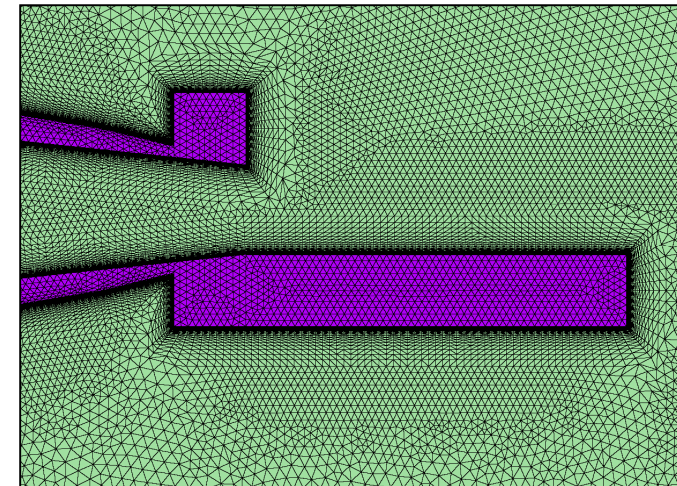
# Grid Generation – FUN3D vs. USM3D



- The same set of grids were used for the FUN3D and USM3D analyses
- Slightly different boundary layer
- USM3D currently cannot handle mixed element grids
- Grid resolution different between the two solvers



FUN3D – Mixed Element Grid

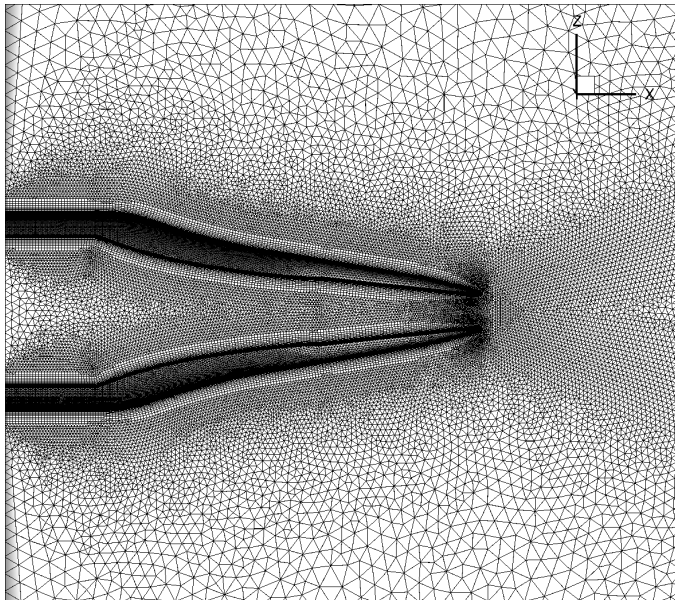


USM3D – Tetrahedral Grid

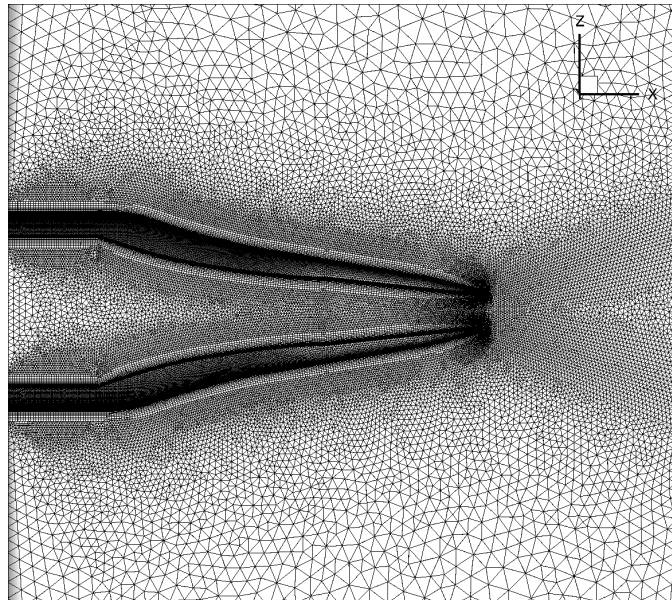
# Grid Sizes – Baseline Nozzle



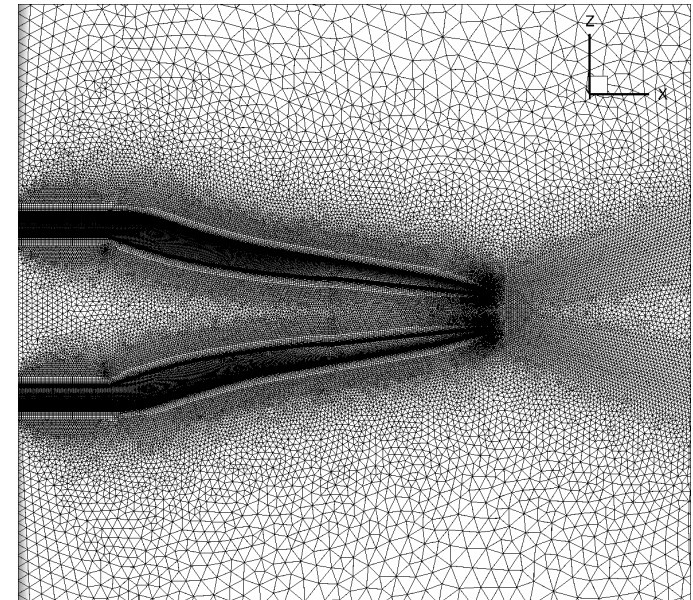
|       | FUN3D      |            |            | USM3D      |            |            |
|-------|------------|------------|------------|------------|------------|------------|
|       | Coarse     | Medium     | Fine       | Coarse     | Medium     | Fine       |
| Cells | 15,369,179 | 21,123,714 | 29,825,361 | 28,543,750 | 38,094,931 | 52,646,243 |
| Nodes | 4,848,179  | 6,467,247  | 8,928,135  | 4,851,342  | 6,464,769  | 8,920,048  |



Coarse – FUN3D



Medium – FUN3D

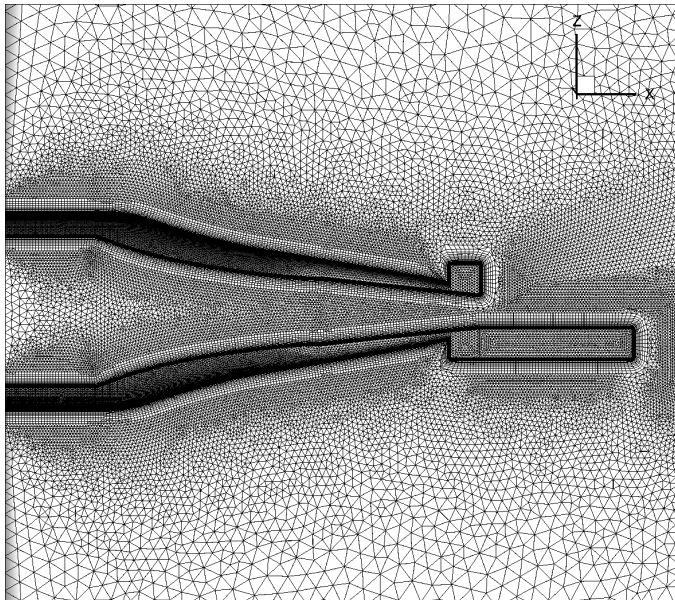


Fine – FUN3D

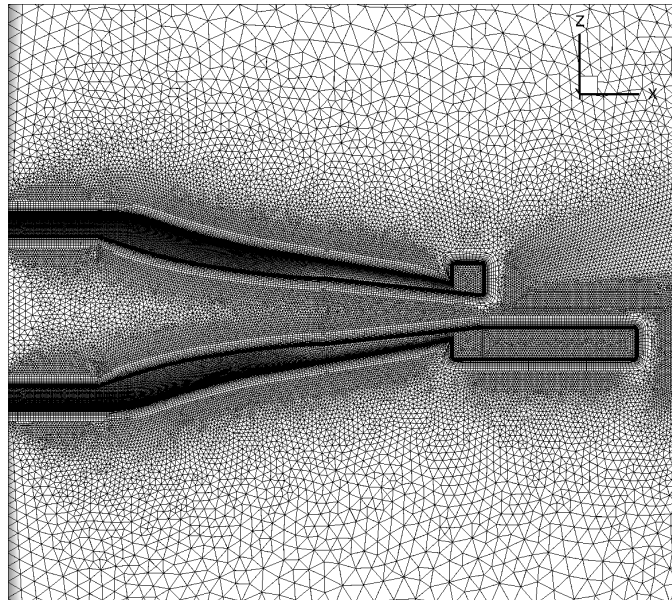
# Grid Sizes – Baseline Nozzle



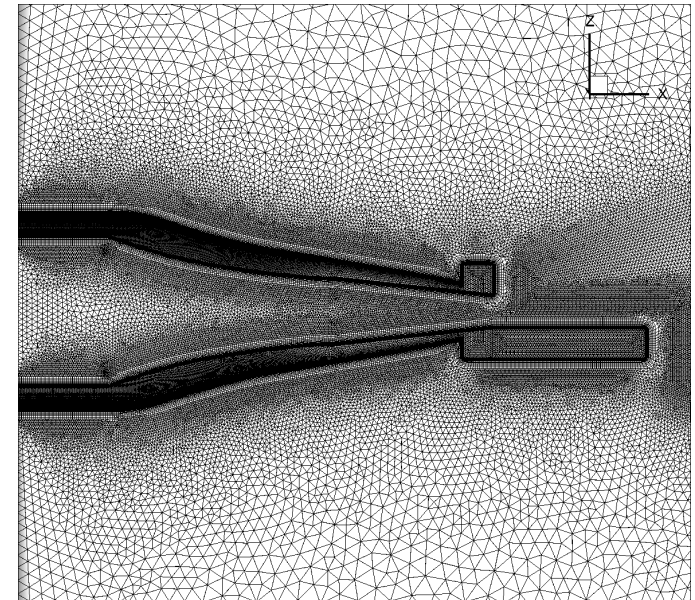
|       | FUN3D      |            |            | USM3D      |            |            |
|-------|------------|------------|------------|------------|------------|------------|
|       | Coarse     | Medium     | Fine       | Coarse     | Medium     | Fine       |
| Cells | 14,360,216 | 20,099,559 | 29,668,187 | 26,569,721 | 35,922,768 | 51,795,206 |
| Nodes | 4,522,151  | 6,099,513  | 8,791,274  | 4,520,385  | 6,099,625  | 8,782,077  |



Coarse – FUN3D



Medium – FUN3D



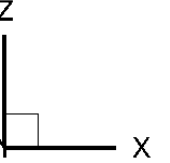
Fine – FUN3D



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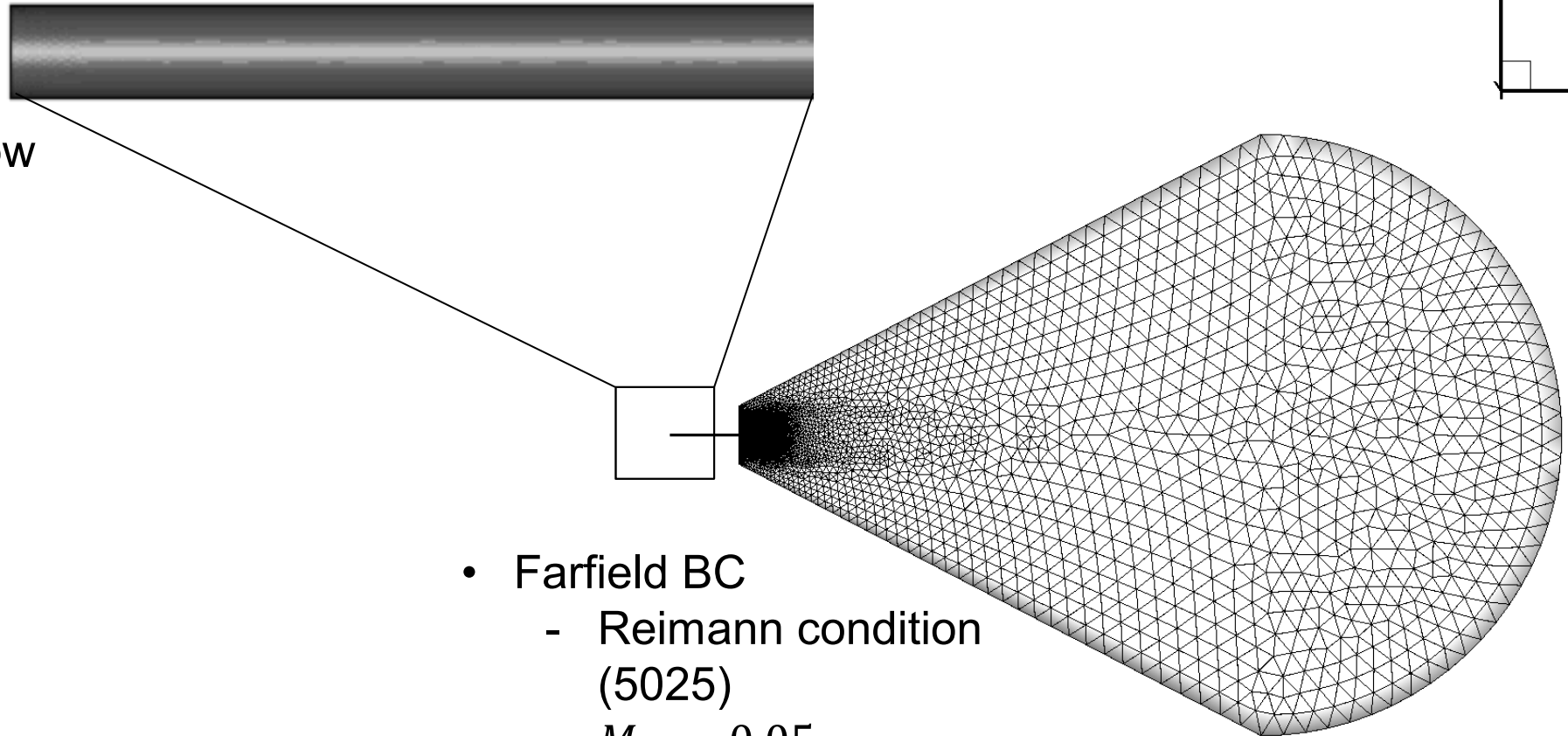
# PROBLEM SETUP

# FUN3D Input



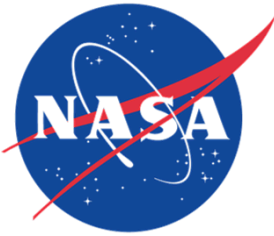
- Inflow BC

- Subsonic inflow (7011)
- $\frac{P_t}{P_\infty} = NPR$
- $\frac{T_t}{T_\infty} = 1.0$



- Farfield BC

- Reimann condition (5025)
- $M_\infty = 0.05$
- $P_\infty = 14.46psi$
- $T_\infty = 504R$



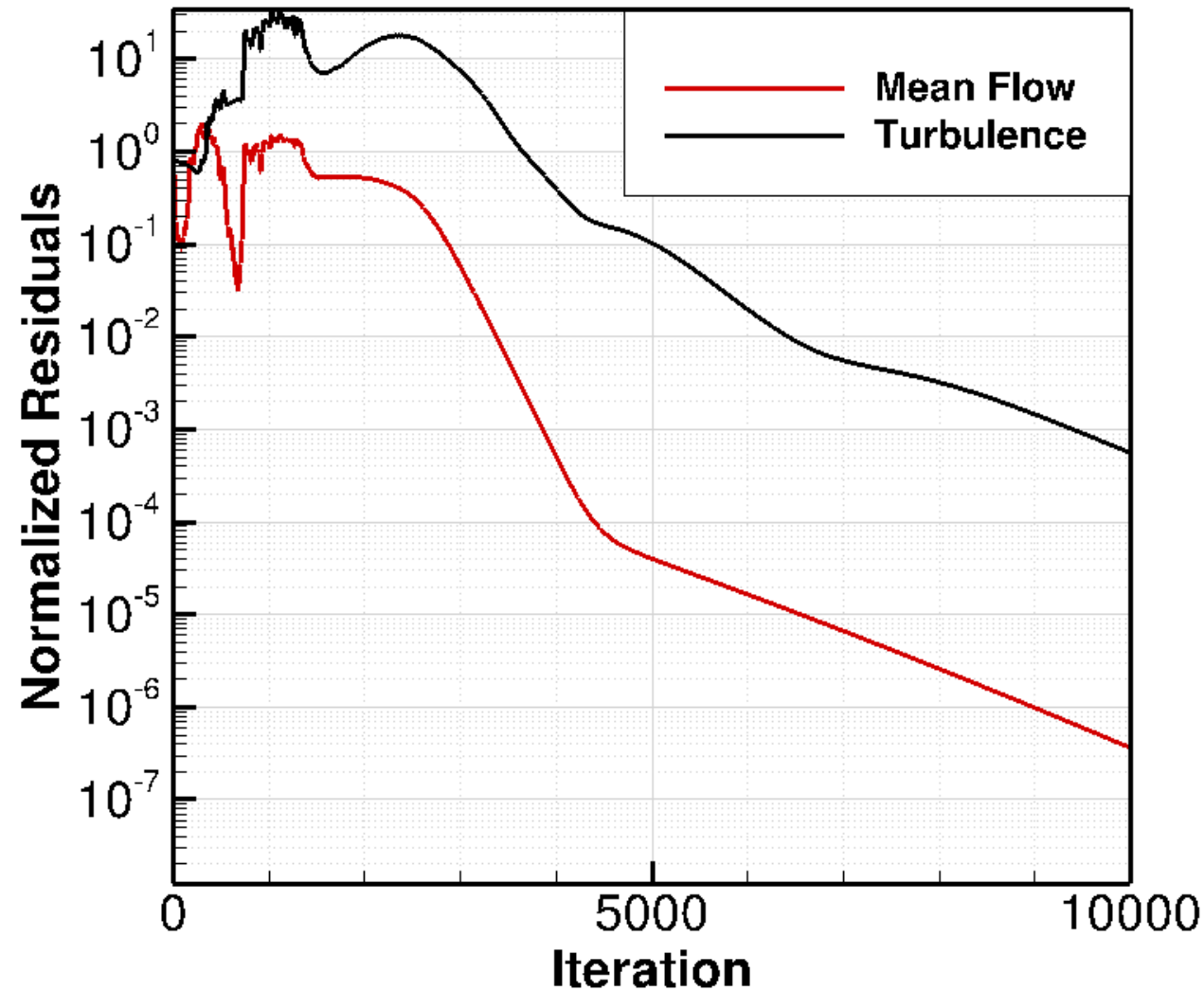
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# RESULTS

# Iterative Convergence - FUN3D



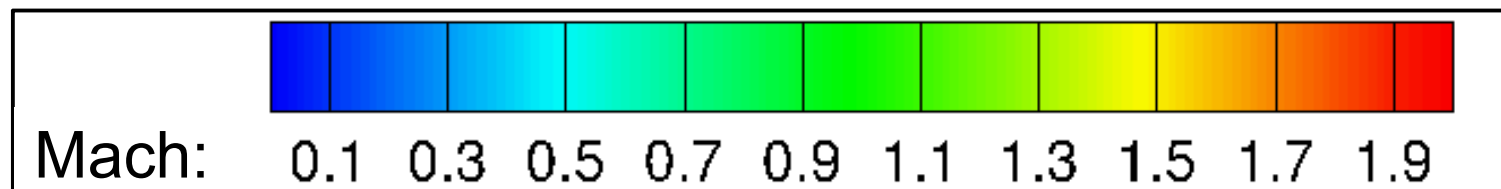
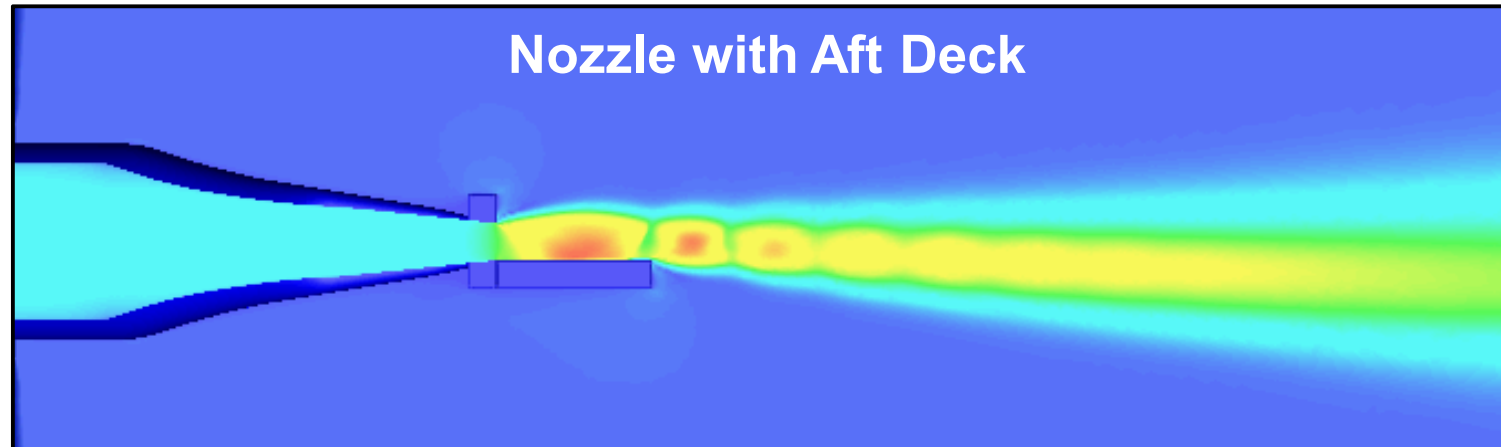
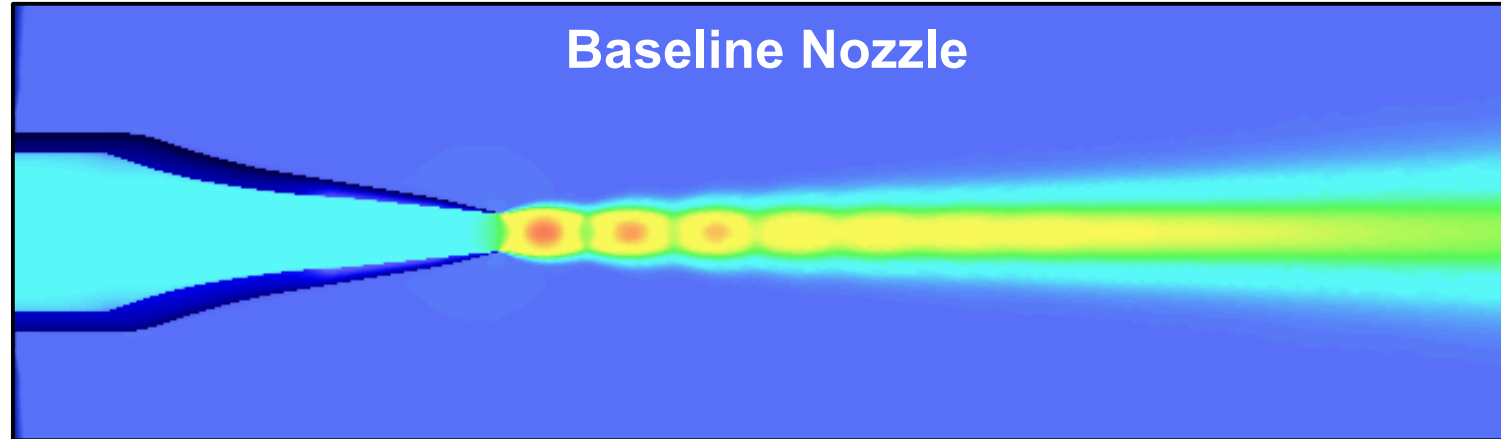
Coarse Grid



# Mach Contours– FUN3D



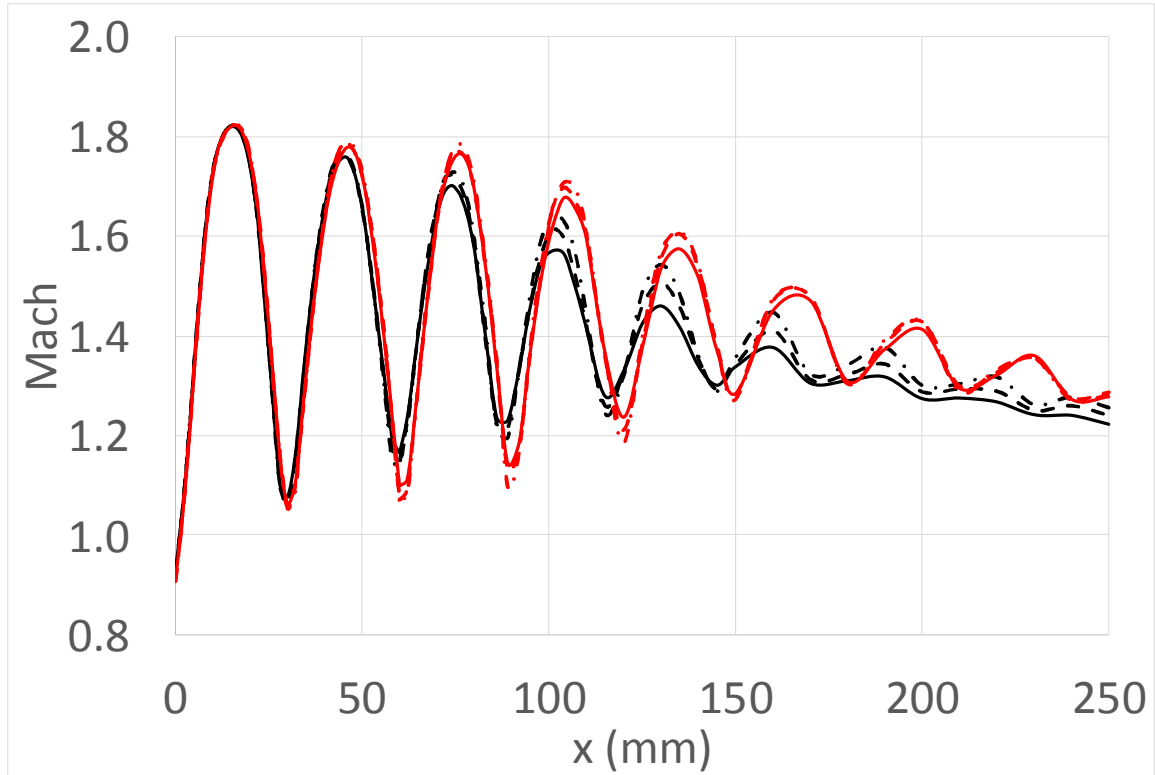
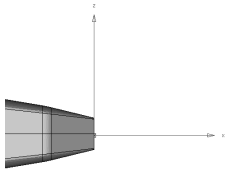
Coarse Grid, NPR = 3.5



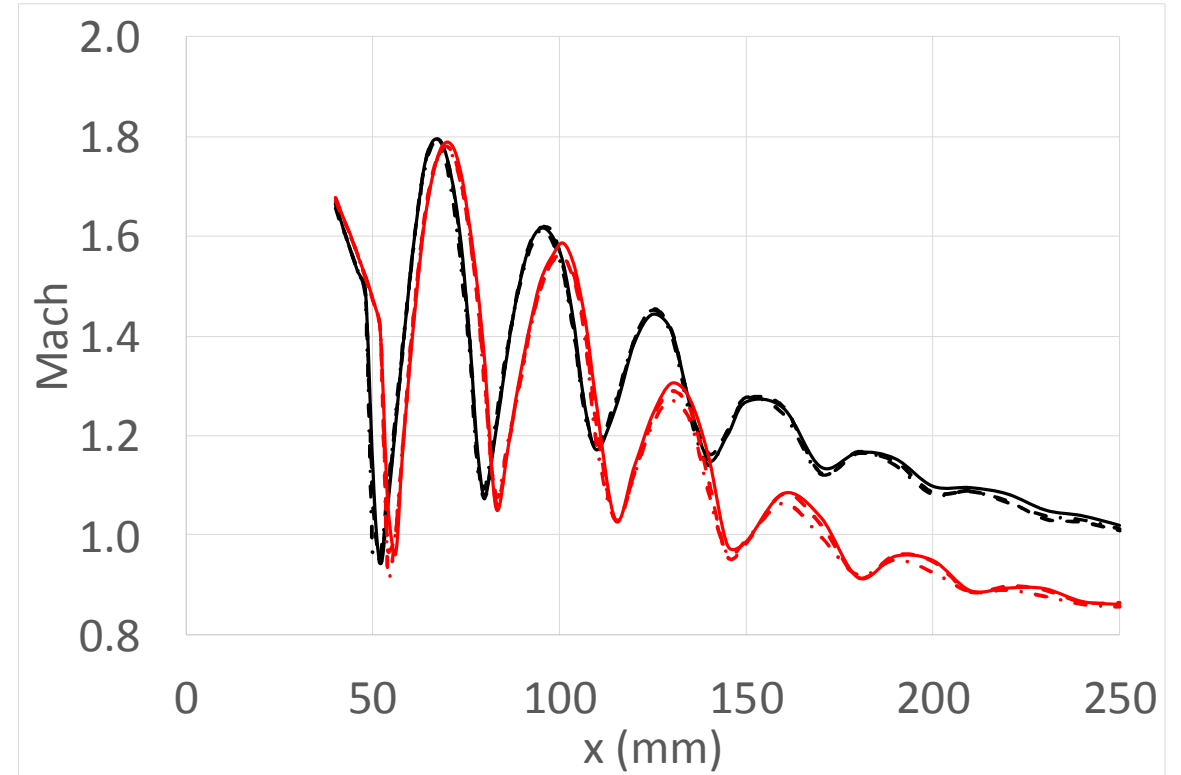
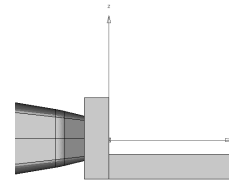


# GRID REFINEMENT STUDY RESULTS

# Centerline Mach Number

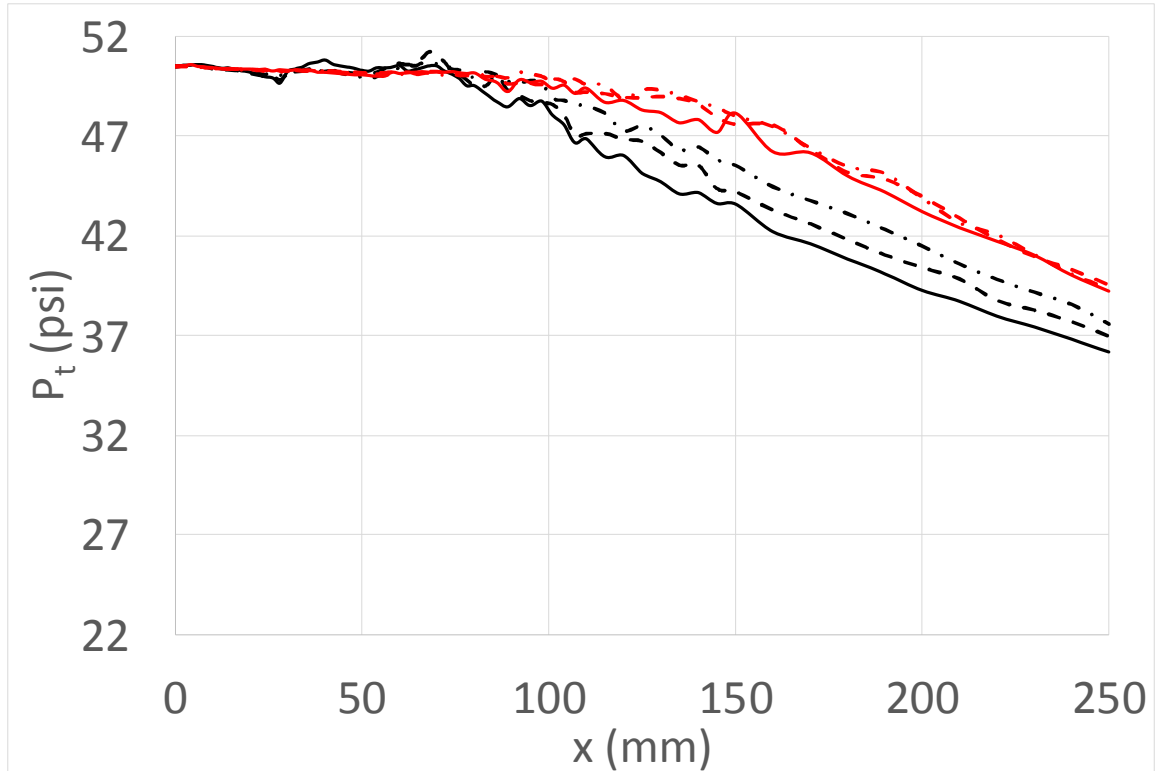
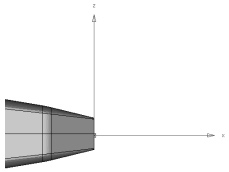


—FUN3D - Coarse  
--FUN3D - Medium  
-·FUN3D - Fine

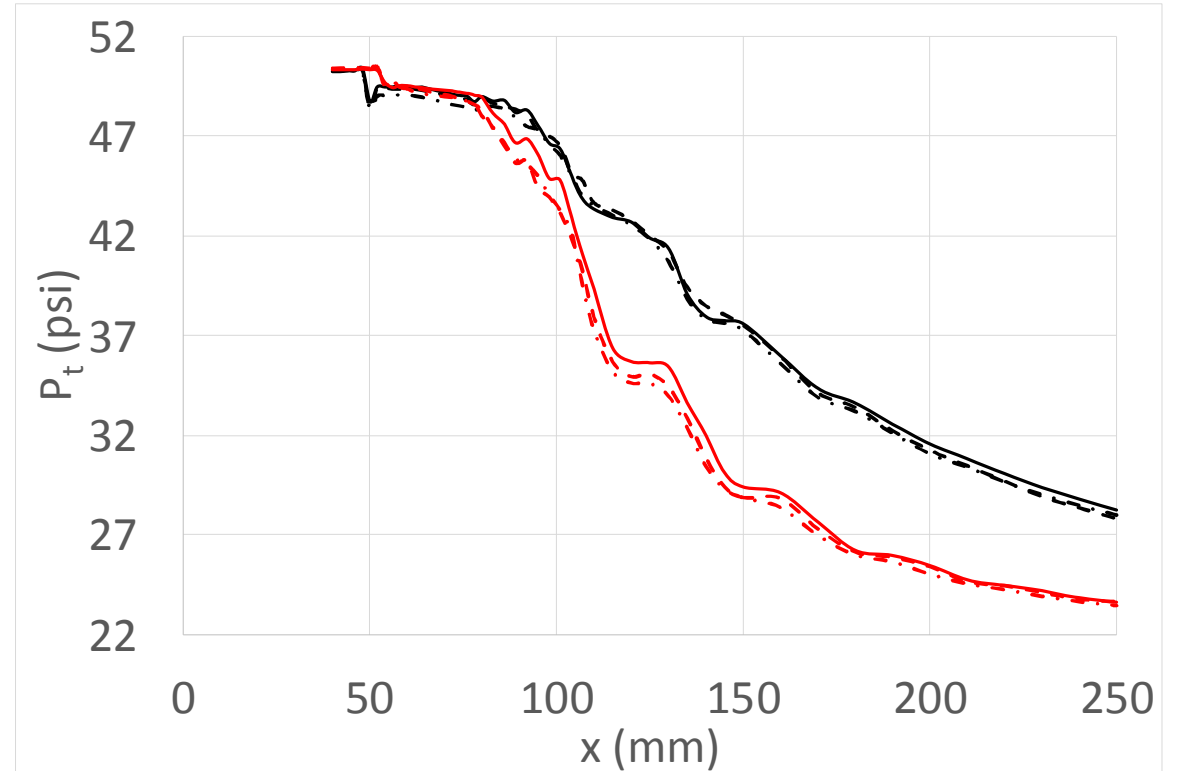
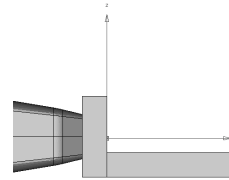


—USM3D - Coarse  
--USM3D - Medium  
-·USM3D - Fine

# Centerline Total Pressure



—FUN3D - Coarse  
--FUN3D - Medium  
-·FUN3D - Fine

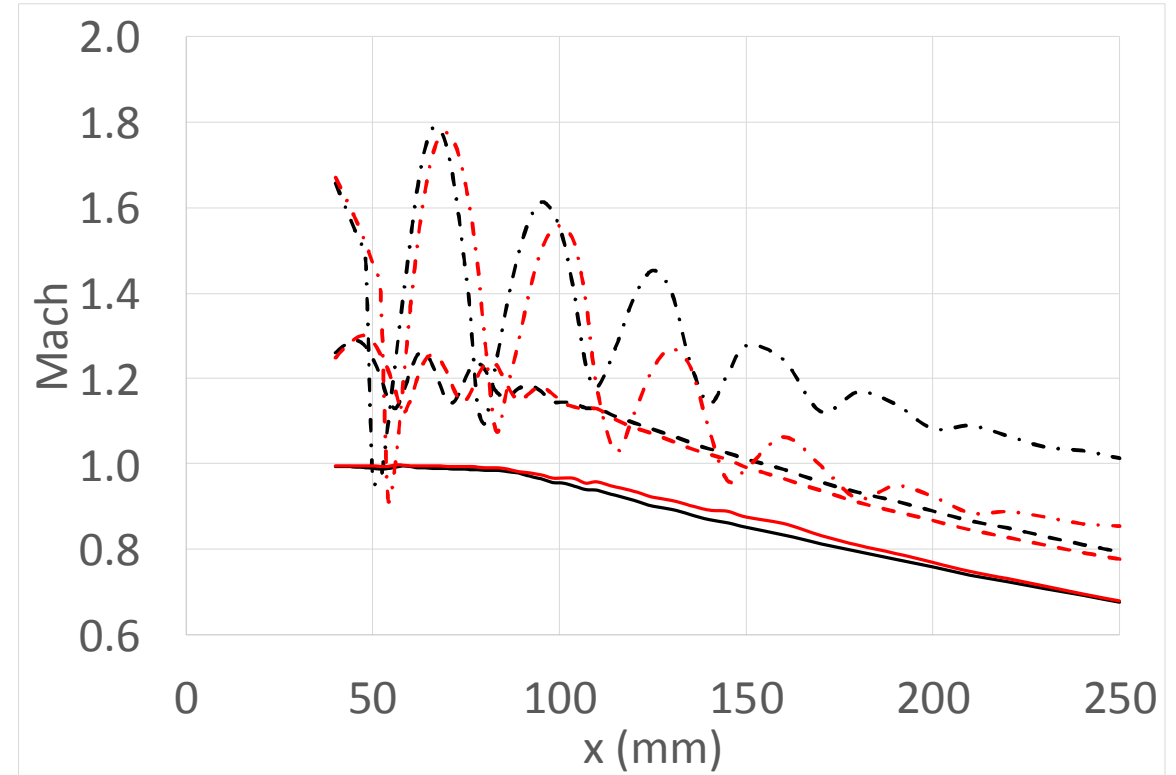
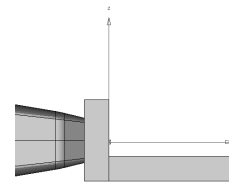
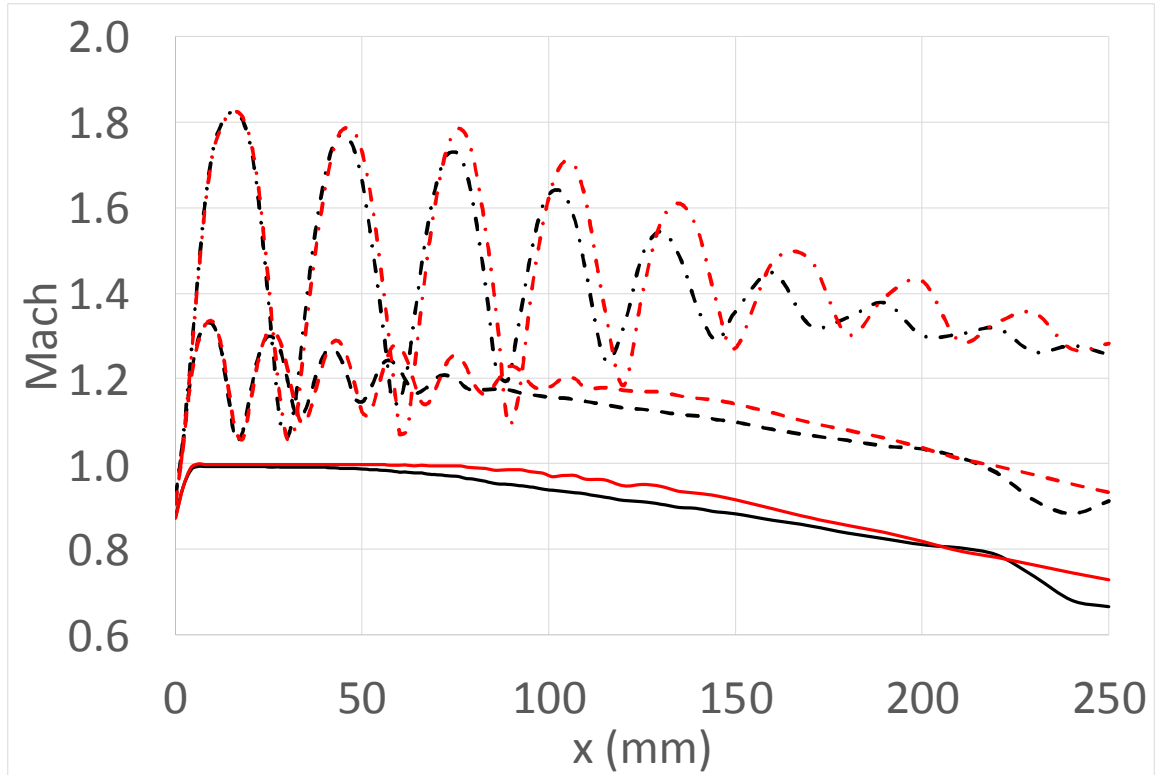
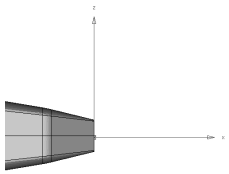


—USM3D - Coarse  
--USM3D - Medium  
-·USM3D - Fine



# NPR COMPARISONS (FINE GRID)

# Centerline Mach Number



—FUN3D - NPR = 1.89

--FUN3D - NPR = 2.45

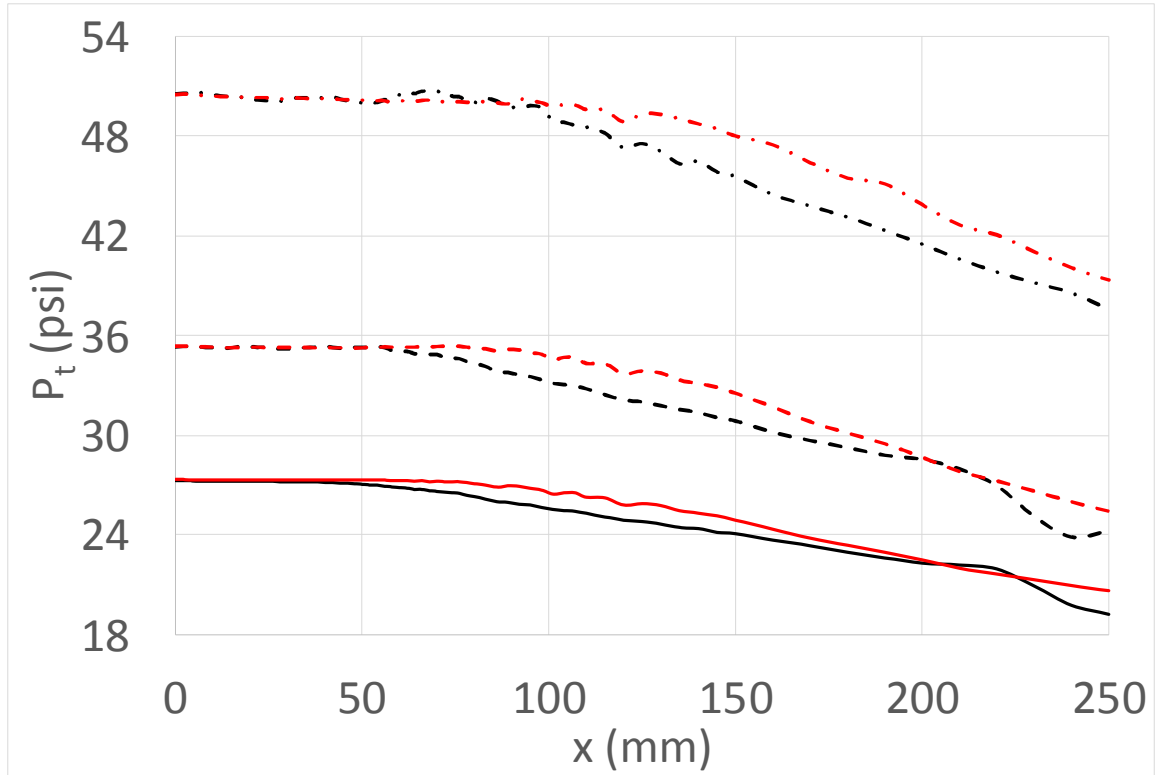
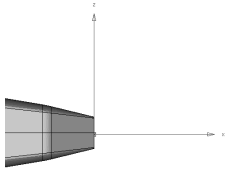
-·FUN3D - NPR = 3.5

—USM3D - NPR = 1.89

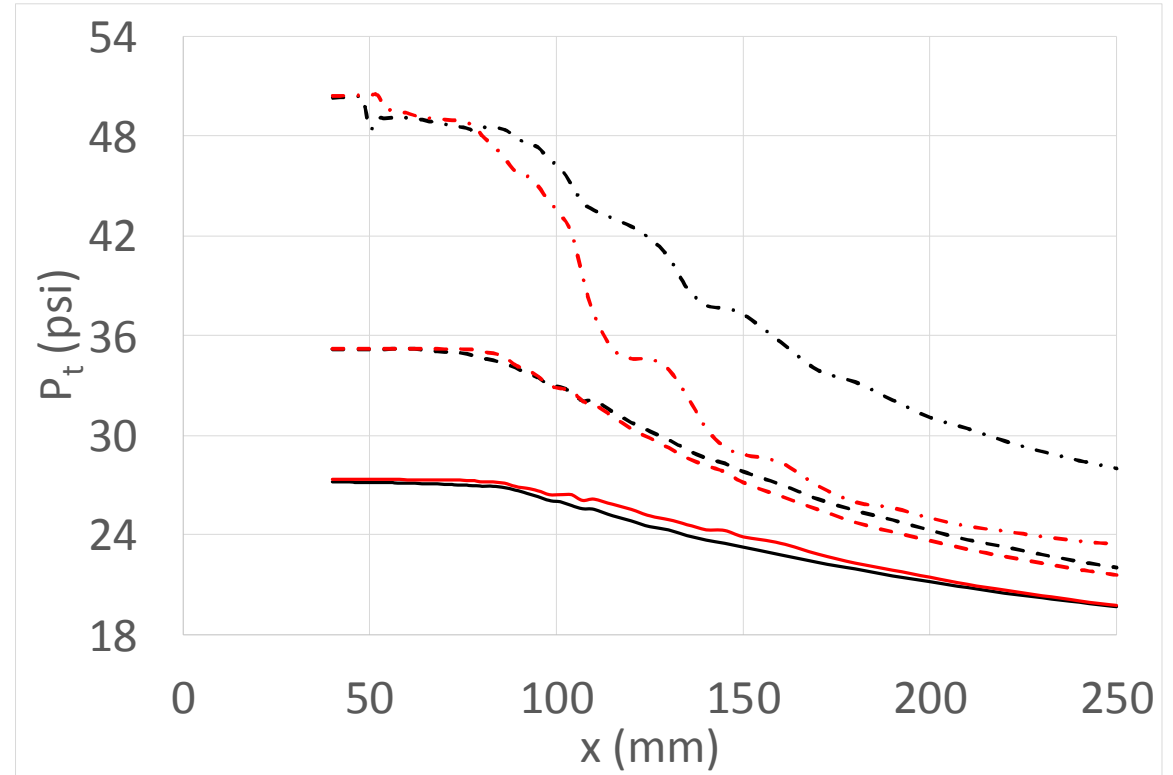
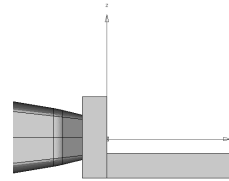
--USM3D - NPR = 2.45

-·USM3D - NPR = 3.5

# Centerline Total Pressure



— FUN3D - NPR = 1.89  
-- FUN3D - NPR = 2.45  
-· FUN3D - NPR = 3.5



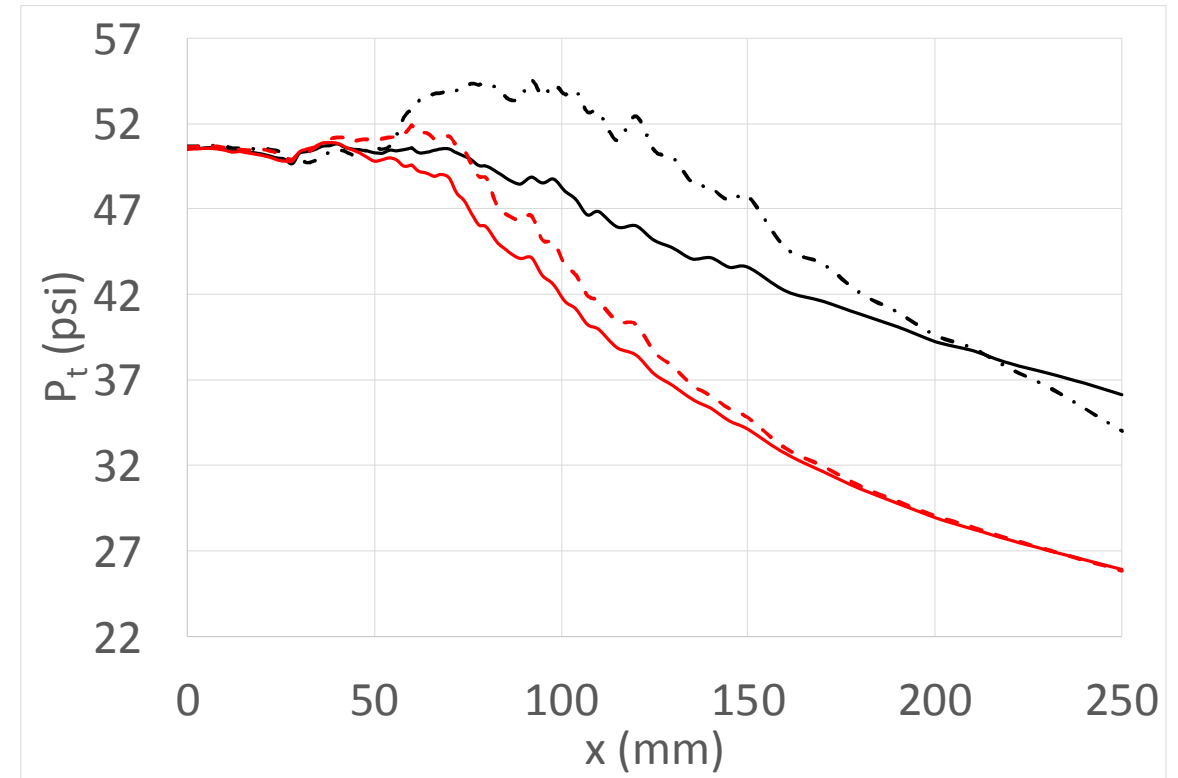
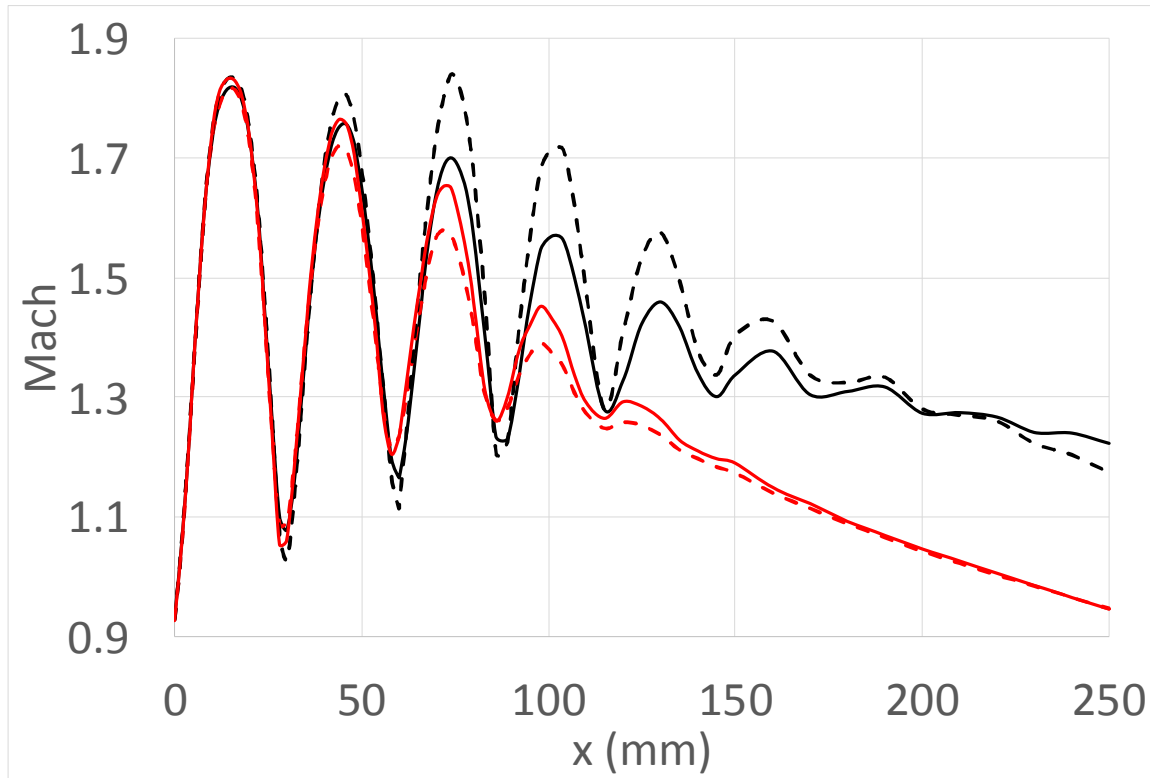
— USM3D - NPR = 1.89  
-- USM3D - NPR = 2.45  
-· USM3D - NPR = 3.5



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# **ADDITIONAL STUDIES – TURBULENCE MODEL AND FLUX LIMITER (COARSE GRID)**

# Baseline Nozzle – FUN3D



—SA w/ Limiter    —SST w/ Limiter  
--SA w/o Limiter    --SST w/o Limiter

# Summary

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- Boundary layer was developed naturally by including upstream duct
- Issues were encountered with farfield boundary requiring the boundary to be moved farther away
- Grid sensitivity study shows very good agreement between the coarse, medium, and fine grids
- FUN3D and USM3D solver results show good agreement close to the nozzle with larger differences downstream
  - Possibly due to grid refinement differences
- Additional studies illustrate significant differences for SA and SST turbulence models

# Questions?

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