Wind-US Results for the AIAA 1st Propulsion Aerodynamics Workshop

This presentation contains Wind-US results presented at the 1st Propulsion Aerodynamics Workshop. The The workshop was organized by the American Institute of Aeronautics and Astronautics, Air Breathing Propulsion Propulsion Systems Integration Technical Committee with the purpose of assessing the accuracy of computational computational fluid dynamics for air breathing propulsion applications. Attendees included representatives from representatives from government, industry, academia, and commercial software companies. Participants were were encouraged to explore and discuss all aspects of the simulation process including the effects of mesh type and mesh type and refinement, solver numerical schemes, and turbulence modeling.

The first set of challenge cases involved computing the thrust and discharge coefficients for a series of convergent convergent nozzles for a range of nozzle pressure ratios between 1.4 and 7.0. These configurations included a included a reference axisymmetric nozzle as well as 15°, 25°, and 40° conical nozzles. Participants were also asked also asked to examine the plume shock structure for two cases where the 25° conical nozzle was bifurcated by a bifurcated by a solid plate. The final test case was a serpentine inlet diffuser with an outlet to inlet area ratio of 1.52 ratio of 1.52 and an offset of 1.34 times the inlet diameter. Boundary layer profiles, wall static pressure, and total and total pressure at downstream rake locations were examined.

Wind-US Results for the AIAA 1st Propulsion Aerodynamics Workshop

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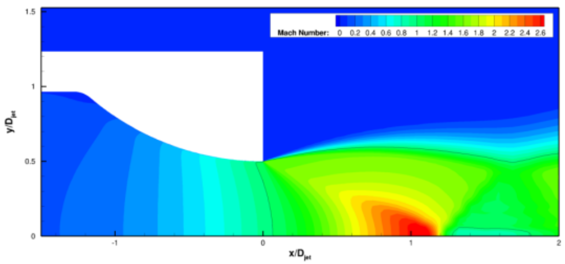
July 29, 2012

Workshop Objectives

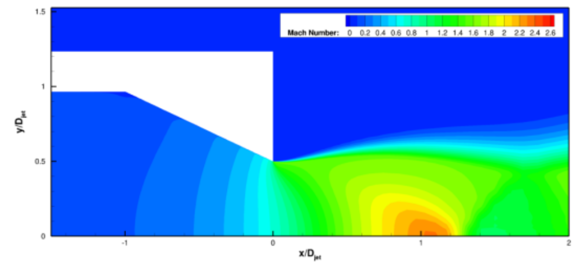
- Assess the accuracy of computational fluid dynamics for air breathing propulsion applications.
  - Surface static pressure predictions
  - Inlet recovery and distortion
  - Nozzle thrust and discharge coefficients
- Assess current numerical prediction capability.
  - (e.g., mesh, numerical schemes, turbulence modeling, computing requirements, and modeling techniques)
- Develop practical guidelines for 2-D and 3-D simulations.
- Select CFD studies will be performed as a **blind trial** and compared with the available experimental data during the workshop.

Workshop Test Cases

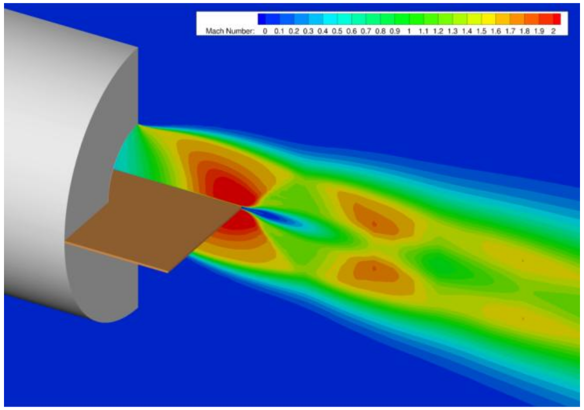
- Reference Axi-Nozzle



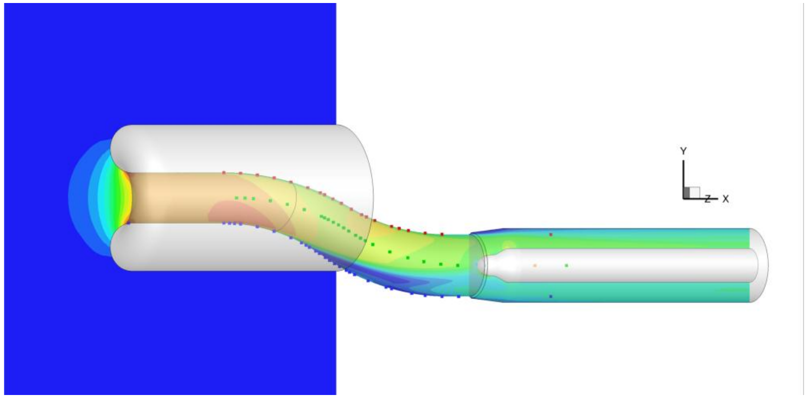
- 15,25,40° Conical Nozzles



- 25° Conical Nozzle with splitter plate



- Serpentine Inlet (S-Duct) [Blind test case]



Workshop Format

- Each group will give a 10 minute presentation for each of the two test cases.
  - Nozzles will be discussed in the morning.
  - S-Duct will be discussed in the afternoon.
- Organizers will present consolidated results versus experimental data and try to summarize the overall findings.
- Select results will be presented at the 2013 AIAA Joint Propulsion Conference.

References

- “An Experimental Study of Compressible Flow Through Convergent-Conical Nozzles, Including a Comparison with Theoretical Results,” R. L. Thornock & E. F. Brown, *Transactions of the ASME Journal of Basic Engineering*, pp. 926-932 , Dec. 1972.

Wind-US Nozzle Results for the AIAA 1st Propulsion Aerodynamics Workshop

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PAW Nozzle Cases

✓ Instance 1 (complete)

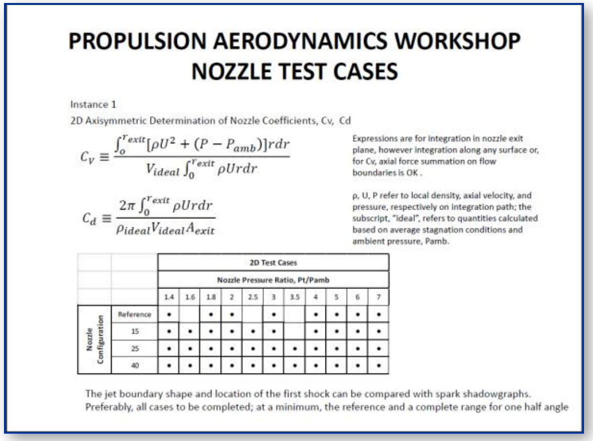
- 4 axisymmetric nozzles (3.0in Dia)
  - Reference
  - 15° conical
  - 25° conical
  - 40° conical
- NPR: 1.4-7.0
- 40 simulations
- Requested data:
  - C_d,C_v
  - M_{wall} on nozzle wall
  - M_{wall} from rake in jet plume

✓ Instance 2 (complete)

- Compare jet plume for NPR=4.0:
  - 25° conical, axisymmetric
  - 25° conical w/Splitter plate
- Requested data: Flowfield p,T,M,θ

✓ Instance 3 (in progress)

- Time-accurate simulation of splitter plate vortex shedding for NPR=1.6
  - 25° conical w/Splitter plate
- Requested data: flowfield snap-shot



PROPULSION AERODYNAMICS WORKSHOP
NOZZLE TEST CASES

Instance 1

2D Axisymmetric Determination of Nozzle Coefficients, Cv, Cd

$$C_V \equiv \frac{\int_o^{r_{exit}}[\rho U^2 + (P - P_{amb})]rdr}{V_{ideal}\int_0^{r_{exit}}\rho U r dr}$$

$$C_d \equiv \frac{2\pi\int_0^{r_{exit}}\rho U r dr}{\rho_{ideal}V_{ideal}A_{exit}}$$

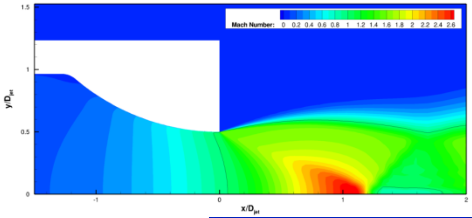
Expressions are for integration in nozzle exit plane, however integration along any surface or, for Cv, axial force summation on flow boundaries is OK .

ρ, U, P refer to local density, axial velocity, and pressure, respectively on integration path; the subscript, "ideal", refers to quantities calculated based on average stagnation conditions and ambient pressure, Pamb.

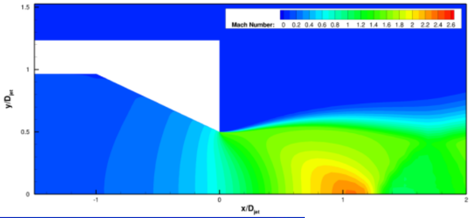
		2D Test Cases										
		Nozzle Pressure Ratio, Pt/Pamb										
		1.4	1.6	1.8	2	2.5	3	3.5	4	5	6	7
Nozzle Configuration	Reference	•		•	•		•		•	•	•	•
	15	•	•	•	•	•	•		•	•	•	•
	25	•	•	•	•	•	•	•	•	•	•	•
	40	•	•	•	•	•	•	•	•	•	•	•

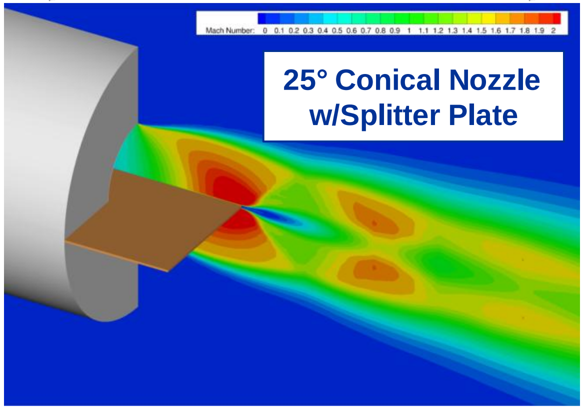
The jet boundary shape and location of the first shock can be compared with spark shadowgraphs. Preferably, all cases to be completed; at a minimum, the reference and a complete range for one half angle

Reference Conical Nozzle



25° Conical Nozzle





Computational Strategy: Solver

- Wind-US v3.165
  - RANS / Hybrid-LES solver
  - Structured and unstructured grids
  - Numerous turbulence models, numerical schemes, and boundary conditions

- All cases:
  - Structured grid solver
  - RANS with SST turbulence model (no compressibility corrections)
  - Roe 2nd-order physical spatial integration scheme (default)
  - Minmod TVD grid flux limiter (default)
  - Inflow: p_0, T_0 held
  - Outflow: p_{inf} held

- Axisymmetic, NPR≤2.0
  - Δt=2.0e-8 s on fine grid

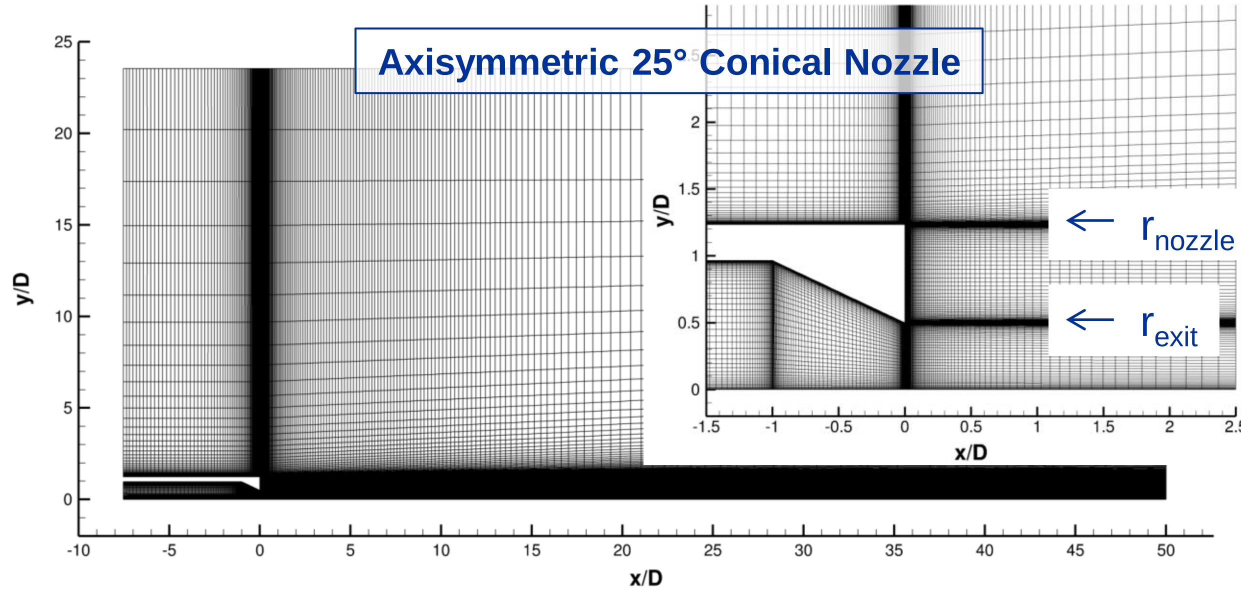
- Axisymmetic, NPR≥2.5
  - CFL#=0.10 on fine grid

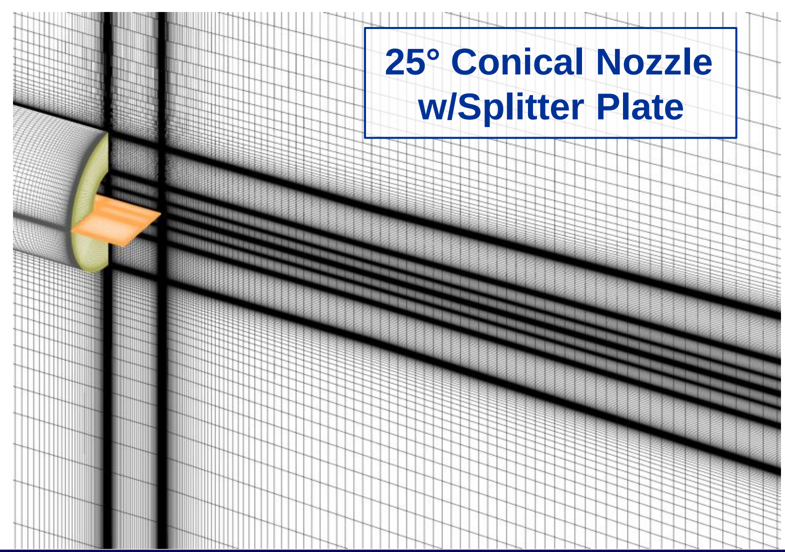
- 3D w/Splitter plate, NPR=1.6
  - Δt=2.0e-8 s on fine grid
  - Fixer mode average for jet plume zones
  - DQ limiter on for jet plume zones
  - Also trying Spalart Detached Eddy Simulation (DES) method

- 3D w/Splitter plate, NPR=4.0
  - CFL#=0.10 on fine grid
  - Fixer mode average for jet plume zones
  - DQ limiter on for jet plume zones

Computational Strategy: Grids

- All Grids
  - Structured, point-matched
  - Created with Pointwise
  - Based on PAW-supplied structured grids
  - $(\Delta s)_{wall}$=1e-4 inches
  - $(\Delta s)_{exit}$=1e-4 inches
- Axisymmetric, Reference:
  - 74,230 grid points
  - 6 zones
- Axisymmetric, Conical:
  - 71,466 grid points
  - 6 zones
- 3D w/Splitter Plate:
  - 14,085,532 grid points
  - 68 zones



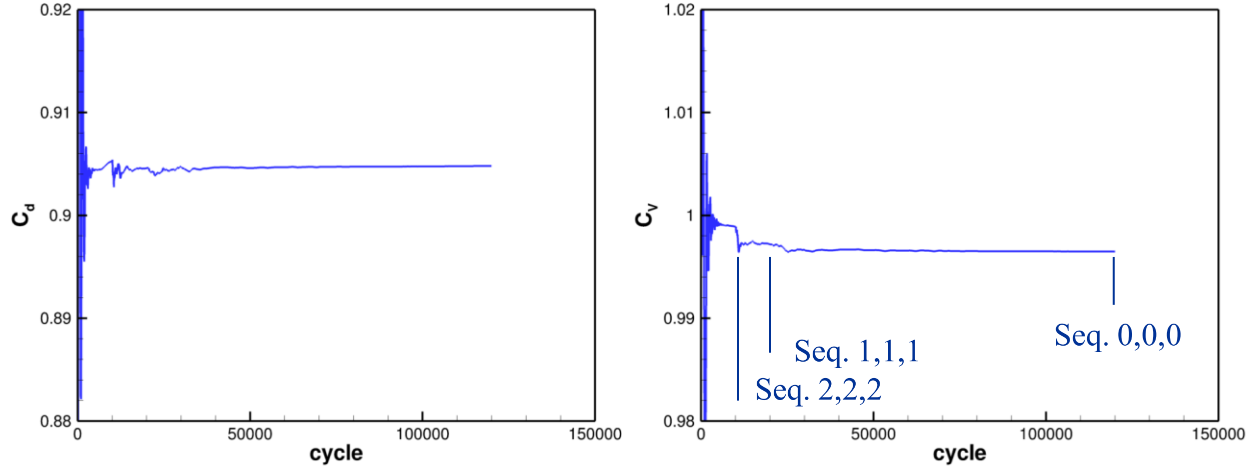


Convergence

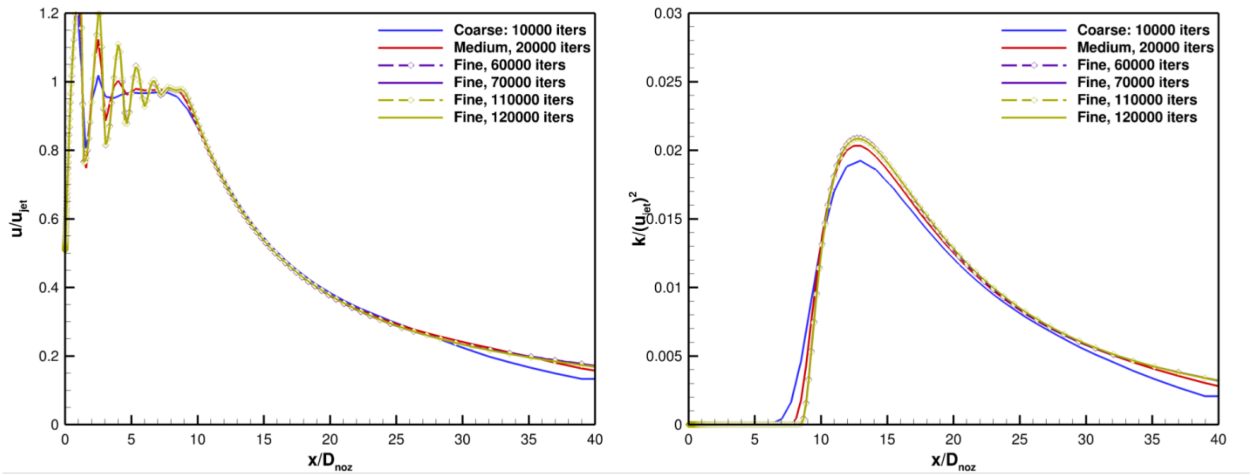
- Sequence grid:
  - Coarse: every 4th point
  - Medium: every 2nd point
  - Fine: all points
- Axisymmetric, constant CFL#:
  - 70,000-120,000 iterations
- Axisymmetric, constant Δt:
  - 300,000-400,000 iterations
- 3D, splitter plate, constant CFL#:
  - 250,000 iterations
- 3D, splitter plate, constant Δt:
  - URANS: 500,000 iterations
  - DES: 420,000 iterations

<u>Shown: 40° conical nozzle w/NPR=4.0.</u> Centerline *u* and *TKE* took longer to converge than C_d and C_V.

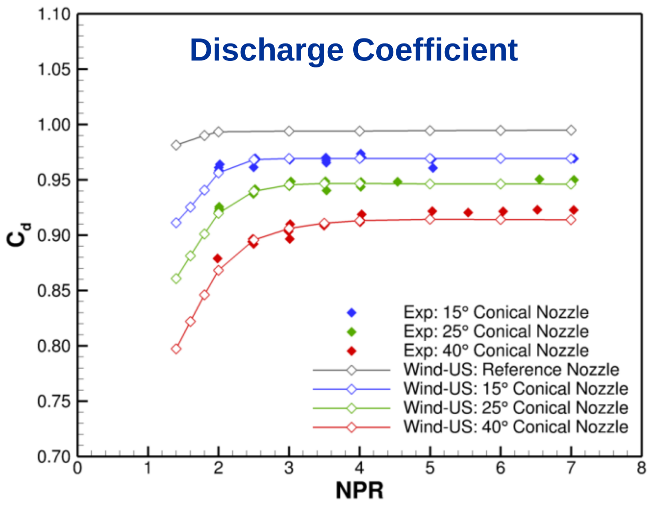
Nozzle Exit: C_d and C_V



Jet Plume: Centerline *u* and *TKE*



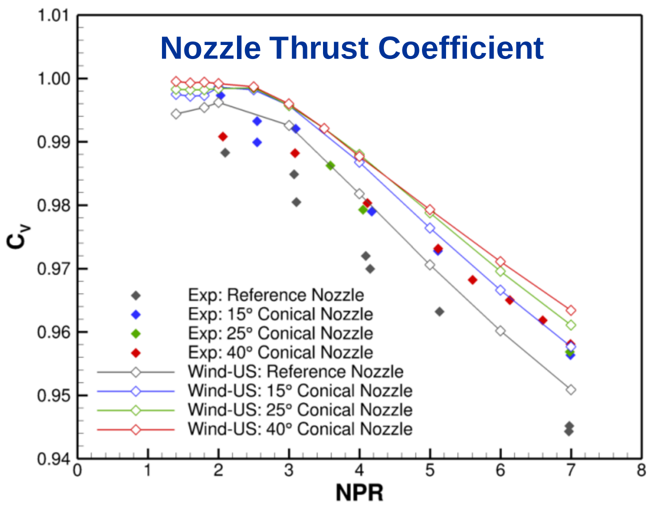
Results: Instance 1

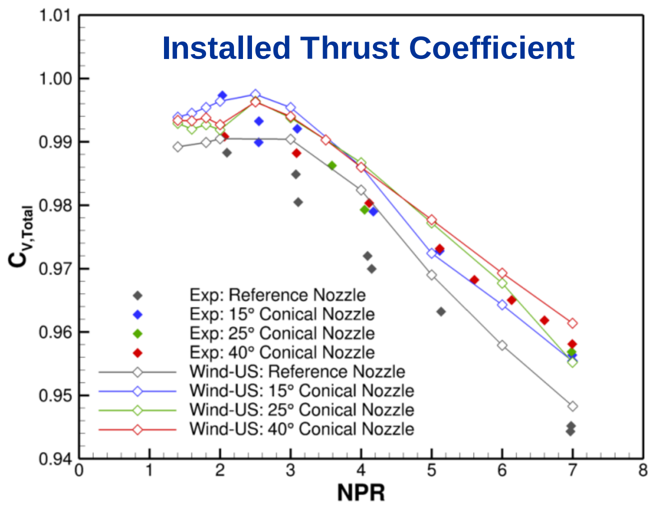


$$C_d \equiv \frac{2\pi \cdot \int_0^{r_{exit}} \rho \cdot u \cdot r \cdot dr}{\rho_{ideal} \cdot U_{ideal} \cdot A_{exit}}$$

$$C_V \equiv \frac{\int_0^{r_{exit}} \left[\rho \cdot u^2 + \left(p - p_\infty\right)\right] \cdot r \cdot dr}{U_{ideal} \cdot \int_0^{r_{exit}} \rho \cdot u \cdot r \cdot dr}$$

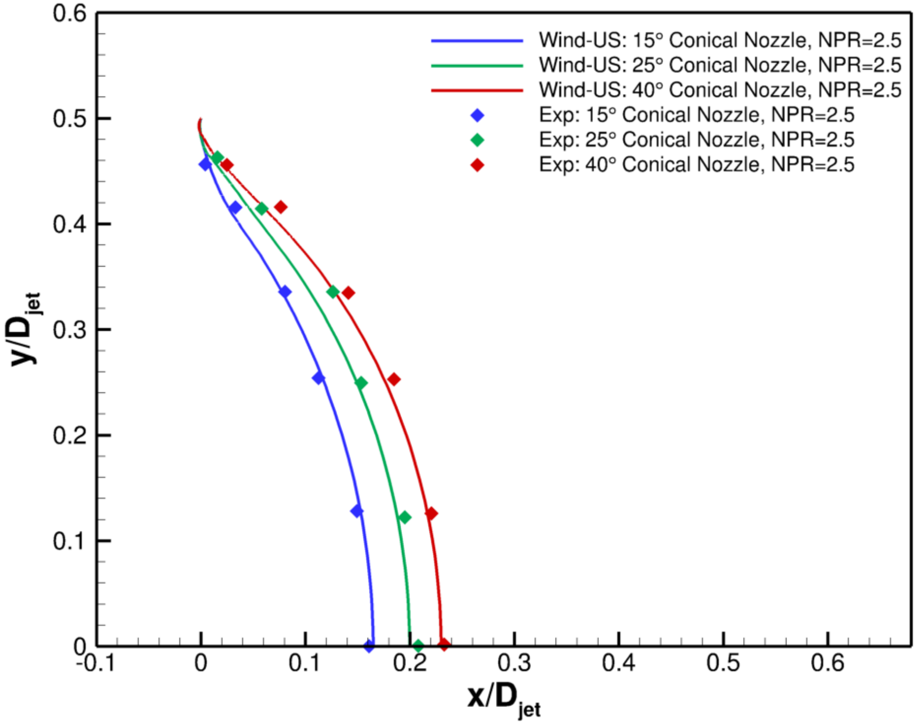
$$C_{V,Total} \equiv \frac{\int_0^{r_{nozzle}} \left[\rho \cdot u^2 + \left(p - p_\infty\right)\right] \cdot r \cdot dr}{U_{ideal} \cdot \int_0^{r_{nozzle}} \rho \cdot u \cdot r \cdot dr}$$

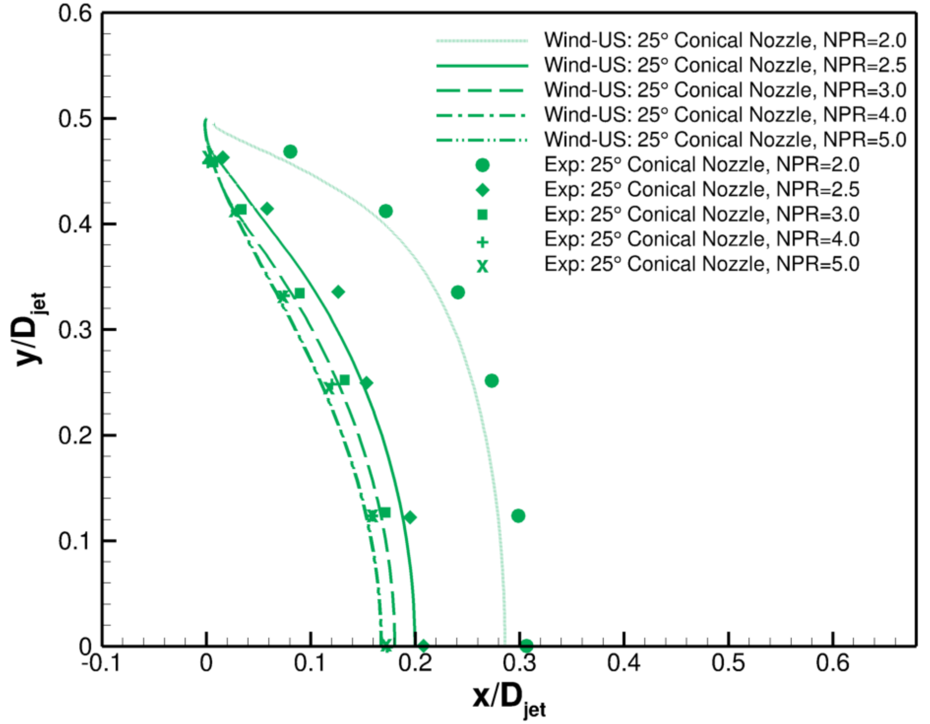




Results: Instance 1

Jet Sonic Lines (Mach=1)

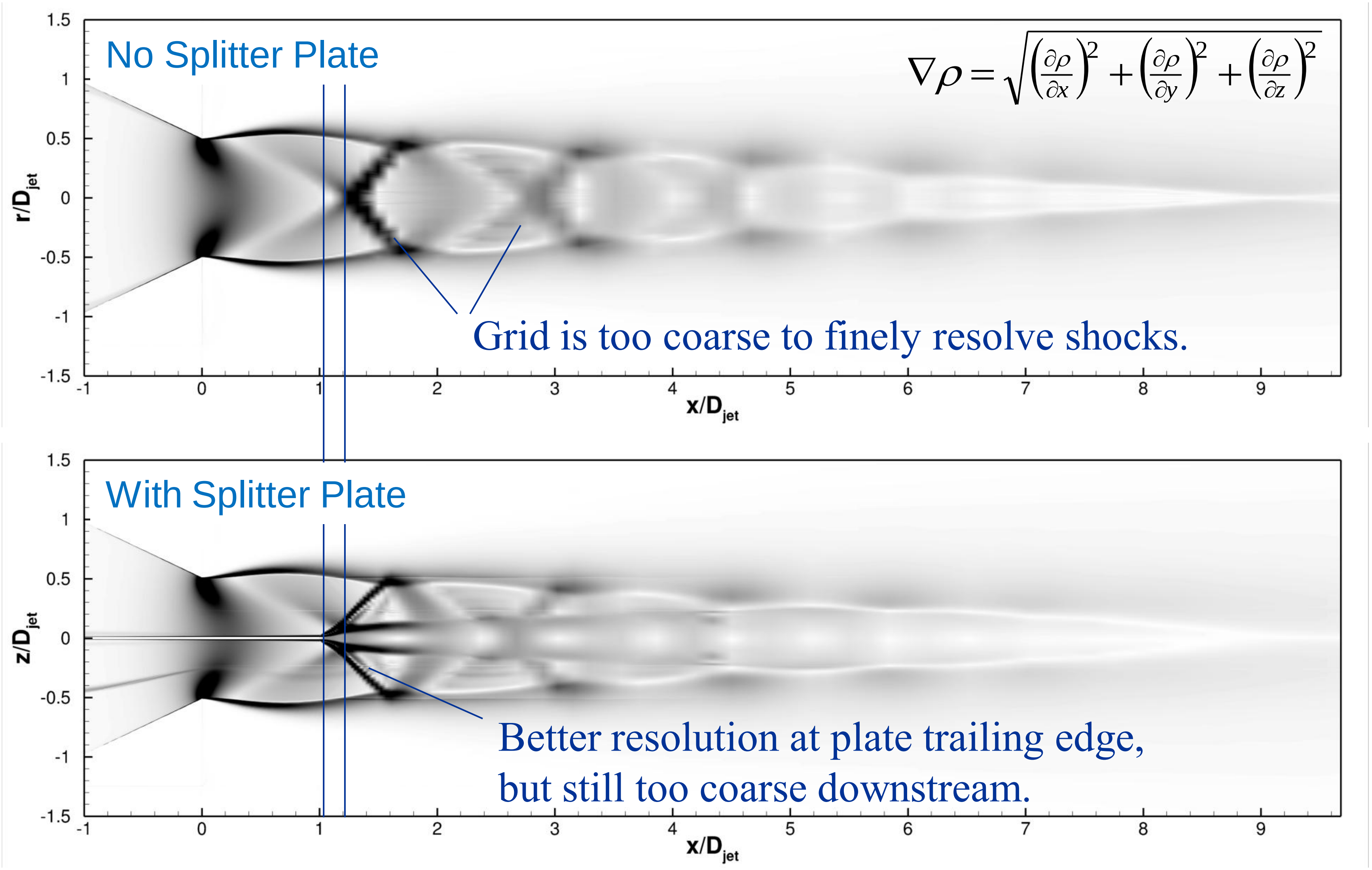




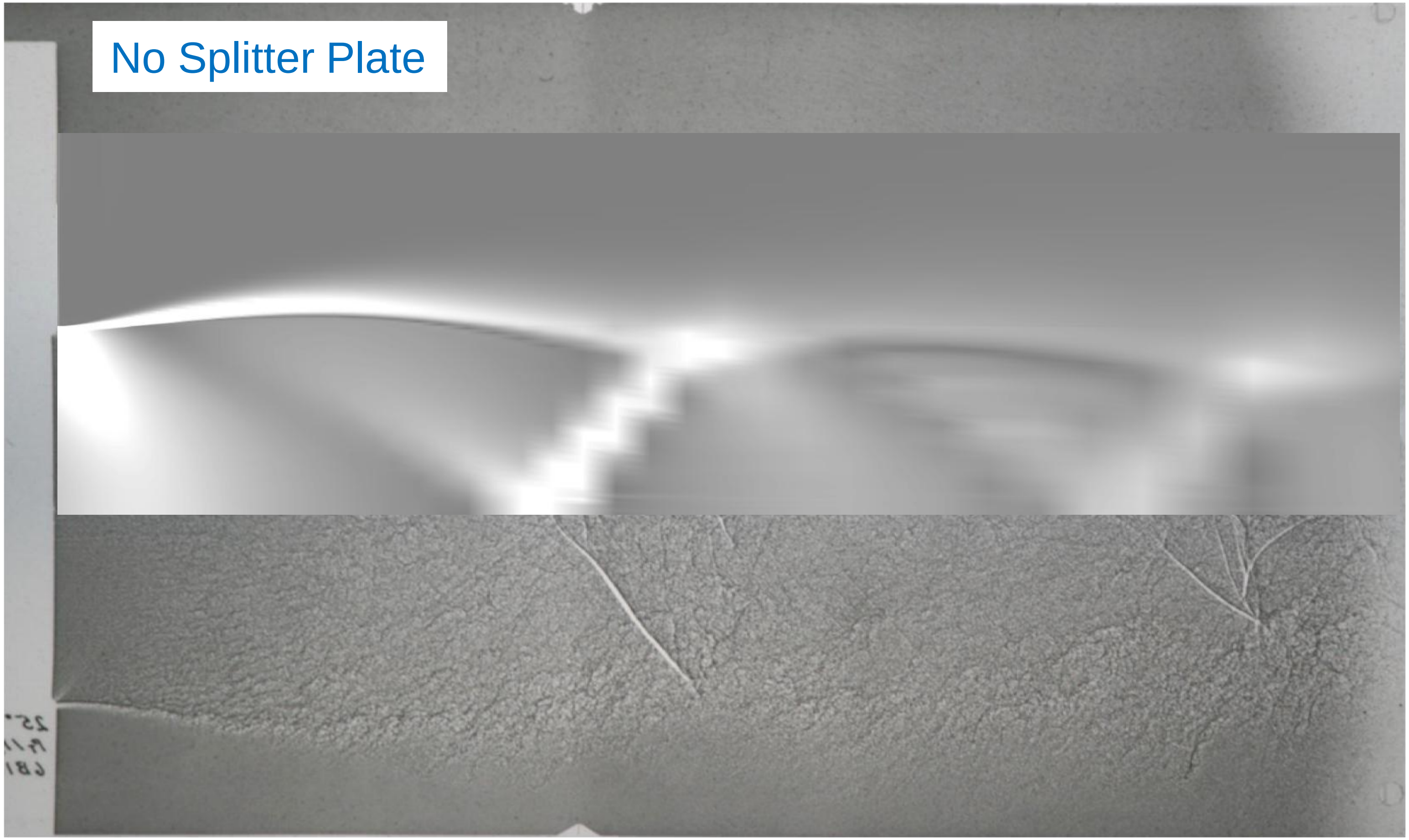
Experimental data from:

Thornock, R. L. and Brown, E. F., "An Experimental Study of Compressible Flow Through Convergent-Conical Nozzles, Including a Comparison With Theoretical Results," *Journal of Basic Engineering*, December 1972.

Results: Instance 2

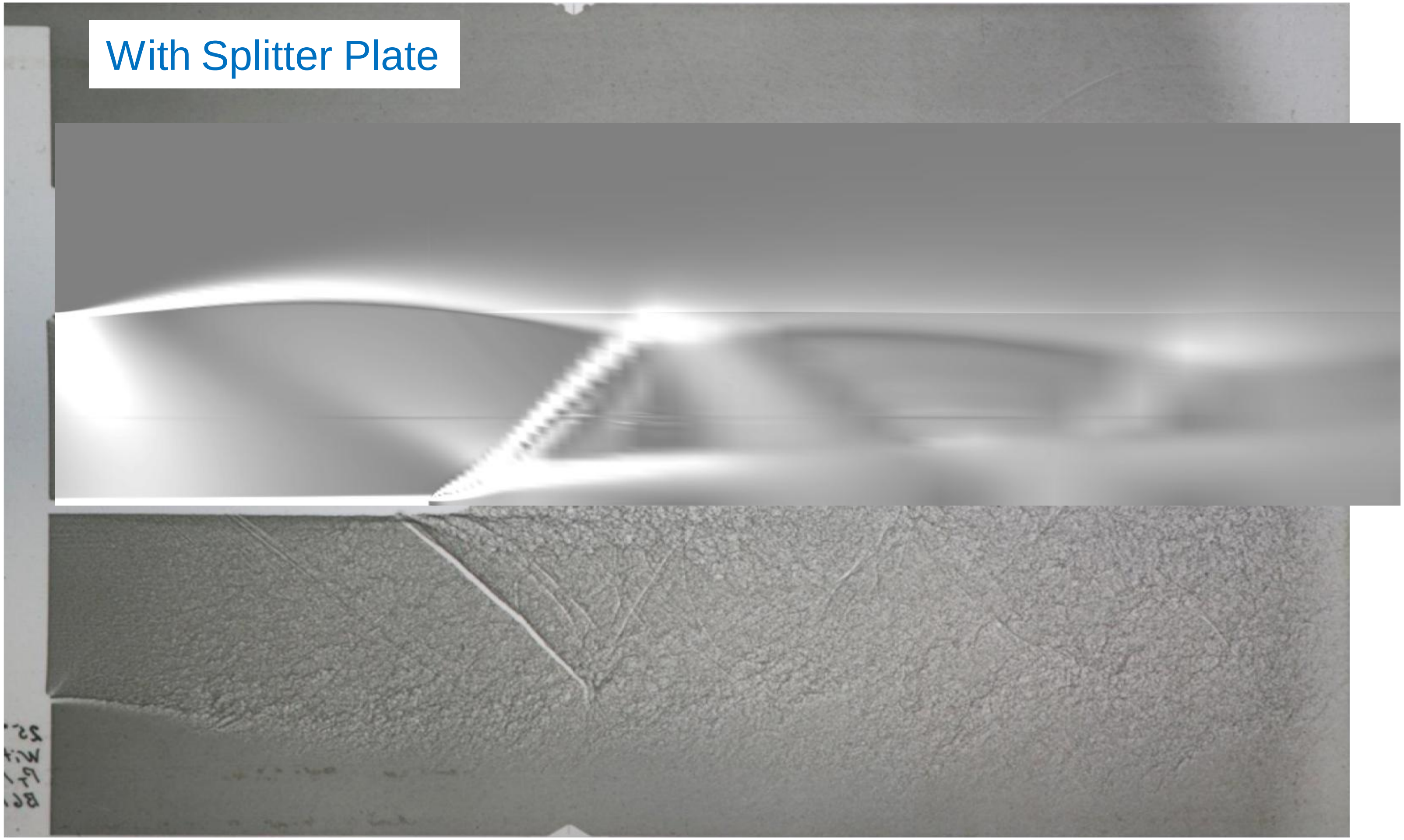


Instance 2: Comparison of Wind-US and Experimental Shadowgraphs



- Wind-US predicts correct locations of shock and expansion waves.
- However, grid through jet plume is too coarse to finely resolve waves.

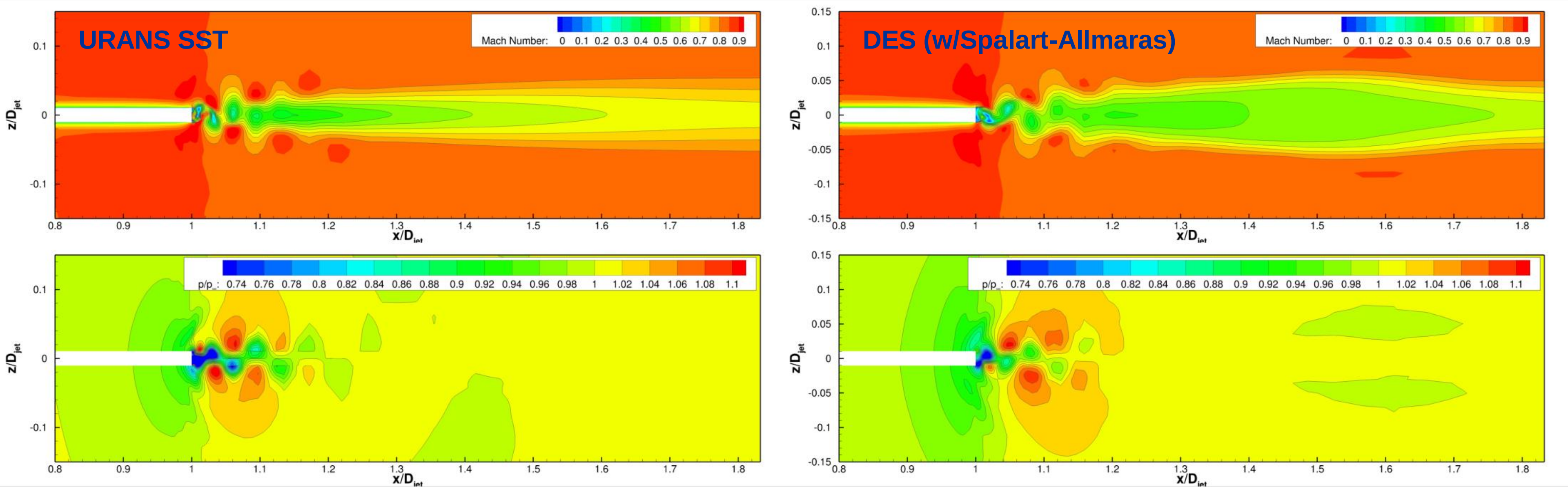
Instance 2: Comparison of Wind-US and Experimental Shadowgraphs



- Grid through jet plume is still too coarse to finely resolve shock and expansion waves.
- Mismatch between Wind-US and experimental wave locations partly due to difficulty in aligning with experimental splitter plate trailing edge location.

Results: Instance 3

Time-accurate unsteady vortex shedding



Notes:

- Solutions assume flow is symmetric; only 180° sector modeled.
- Instantaneous solutions shown.
- Downstream mesh (x/D>1.2) is too coarse to resolve vortical structures.

Challenges

- For NPR≤2.0, solutions showed unsteadiness when running with constant CFL#.
  - Used constant time step to obtain steady solution. Convergence required 3-4 times as many iterations.

- For NPR≥5.0, region of unphysically large *TKE* increase along centerline following Mach disk, $2D_{jet}$ downstream of nozzle exit.
  - This is a known deficiency of k-ω based turbulence models (including SST model).
  - Assumed minimal impact on solution near nozzle exit.

- The provided 3D grid with splitter plate had the symmetry plane aligned with the splitter plate.
  - This seemed a poor choice for observing unsteady vortex formation from splitter plate.
  - Modified the grid such that the symmetry plane is perpendicular to the splitter plate.

- Unsteady vortex shedding in Instance 3 required long run times.

Wind-US S-Duct Results for the AIAA 1st Propulsion Aerodynamics Workshop

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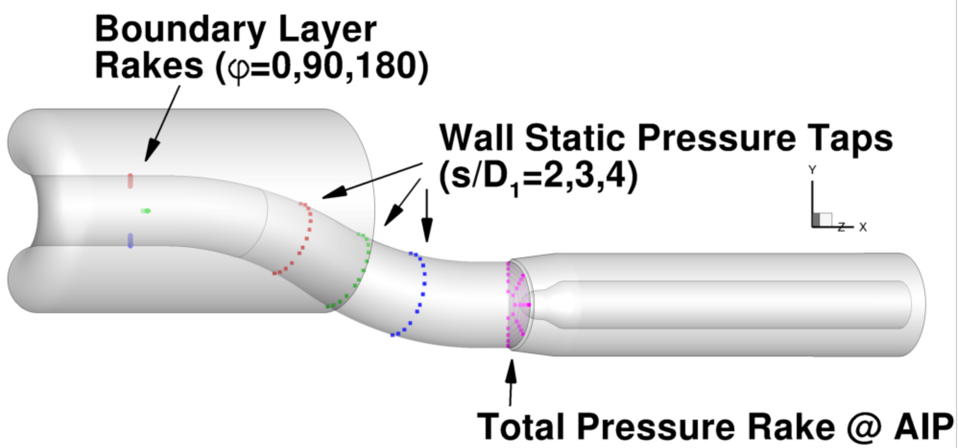
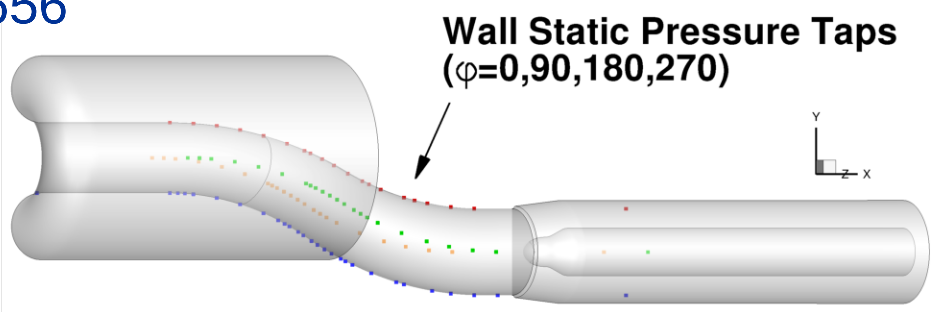
July 29, 2012

S-Duct Problem Description

- Geometry
  - D1 = 133.15 mm
  - D2 = 164.00 mm
  - Area Ratio = 1.52
  - Length = 5.23 * D1
  - Offset = 1.34 * D1



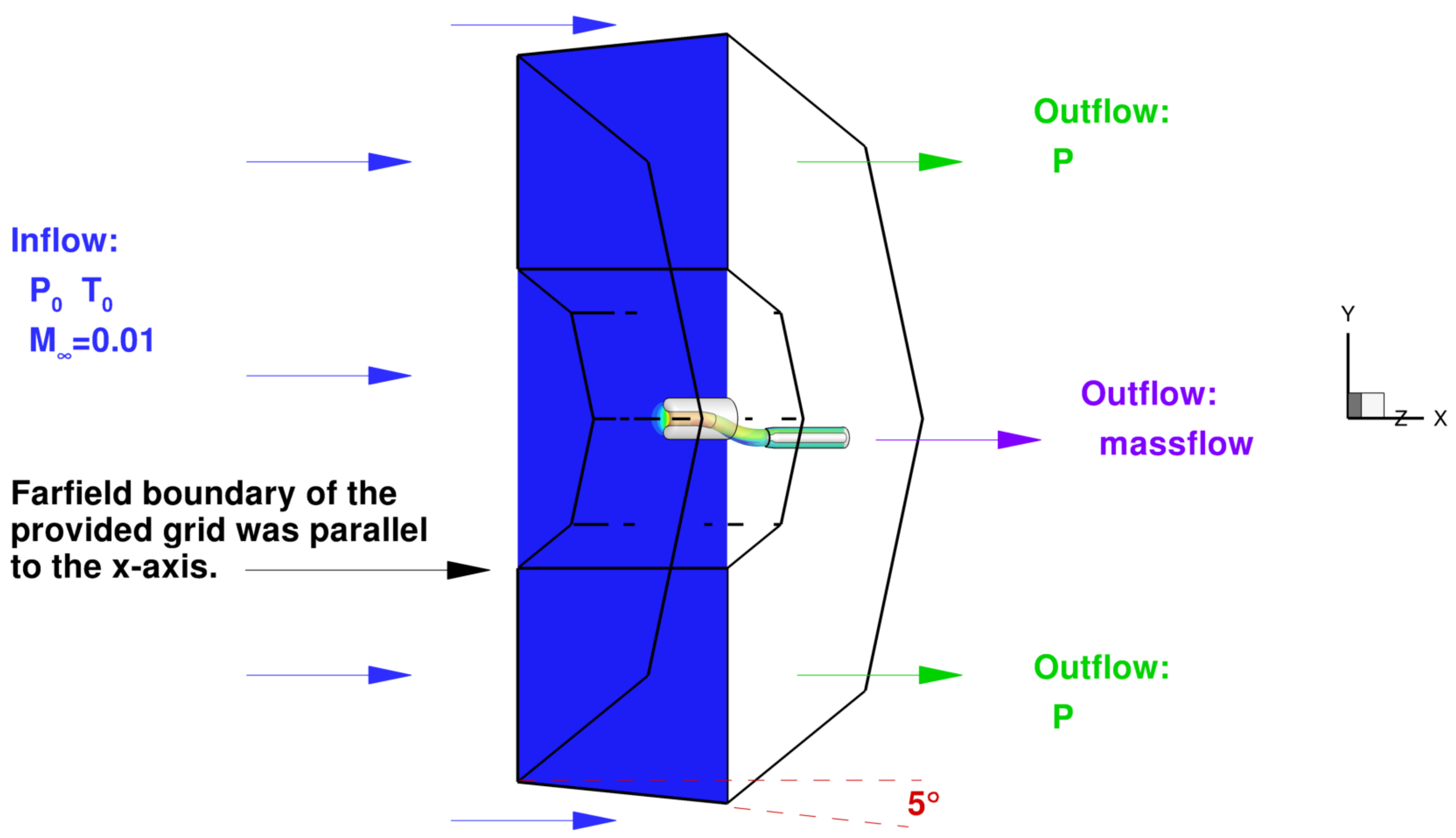
- Flow Conditions
  - Tested in the R4MA facility at ONERA in 2006. Run 1112, Data Point 656
  - Stag P = 88744 Pa
  - Stag T = 286.2 K
  - massflow = 2.427 kg/s (for full 360°)
  - AIP Mach = 0.3549



Wind-US

- For this study,
  - Wind-US Version 3.167
  - Use symmetry & only model half of the geometry
  - Structured, point-matched grids
  - Inflow: Specified total conditions, Mach 0.01
  - Outflow: Specified mass flow 2.427 kg/s * 0.5 (symmetry)
  - Turbulence models
    - Menter Shear Stress Transport (SST)
    - Rumsey-Gatski Algebraic Stress Model (ASM) k-ε
    - Spalart-Allmaras (S-A)
      - Standard model without curvature correction
- Full description of code features:
  - http://www.grc.nasa.gov/WWW/wind/index.html

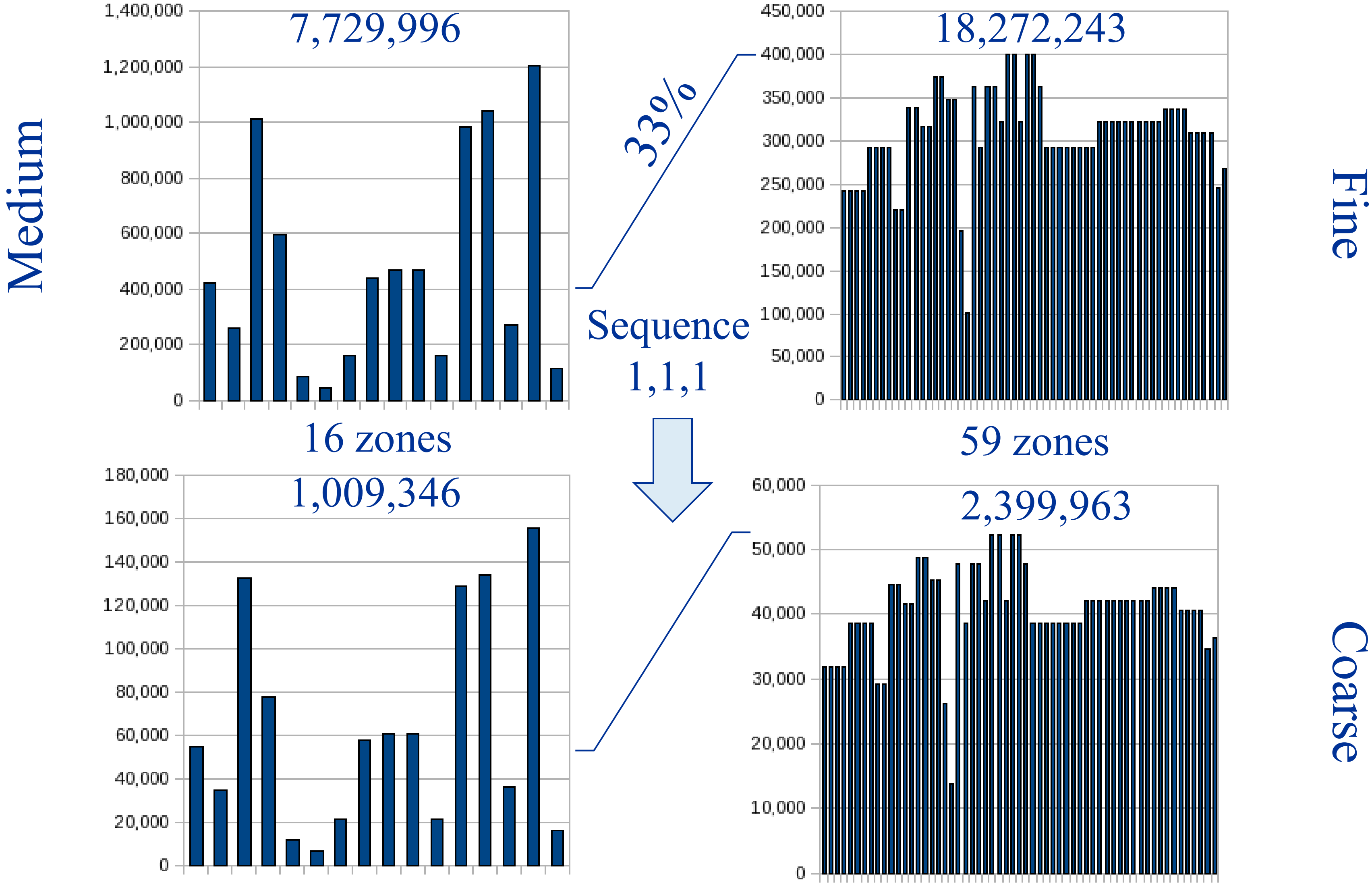
Boundary Conditions



Grids

- Modified the point-matched (medium) grid provided.
  - Added a far-field block with non-parallel boundary.
  - Improved sequencing and adjusted clustering functions.
    - 7,729,996 points (16 zones)
    - 0.0020 mm wall spacing (y^+ of 1.50)
- Fine grid (33% more points in each direction).
  - Made by redimensioning and reclustering the medium grid.
    - 17,968,012 points (16 zones further split to 58 zones)
    - 0.0015 mm wall spacing (y^+ of 1.15)
  - Solutions not completed in time for inclusion.
- Coarse grid (33% less points in each direction).
  - Equal to every other point of the fine grid.
    - 2,321,930 points (16 zones further split to 58 zones)
    - 0.0030 mm wall spacing (y^+ of 2.50)

Improved Zone Balancing

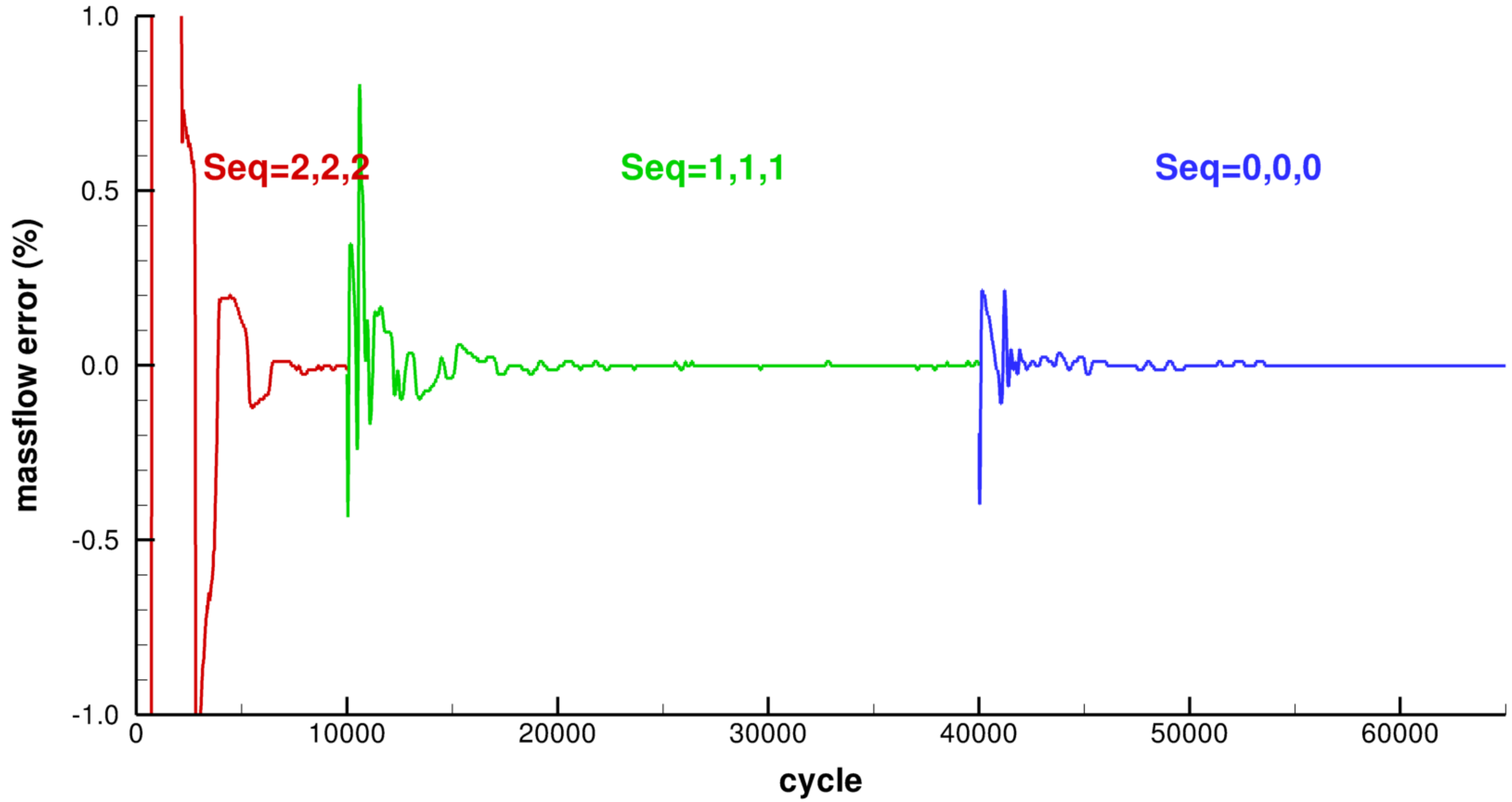


Challenges

- Time & computing constraints
- IGES model defects
  - Multiple (conflicting) curves
  - Imperfect connectivity
- Maintaining database compliance, particularly after modifying the grid with Gridgen.
- Convergence to “steady-state”.
  - Solutions shown here have not been averaged.

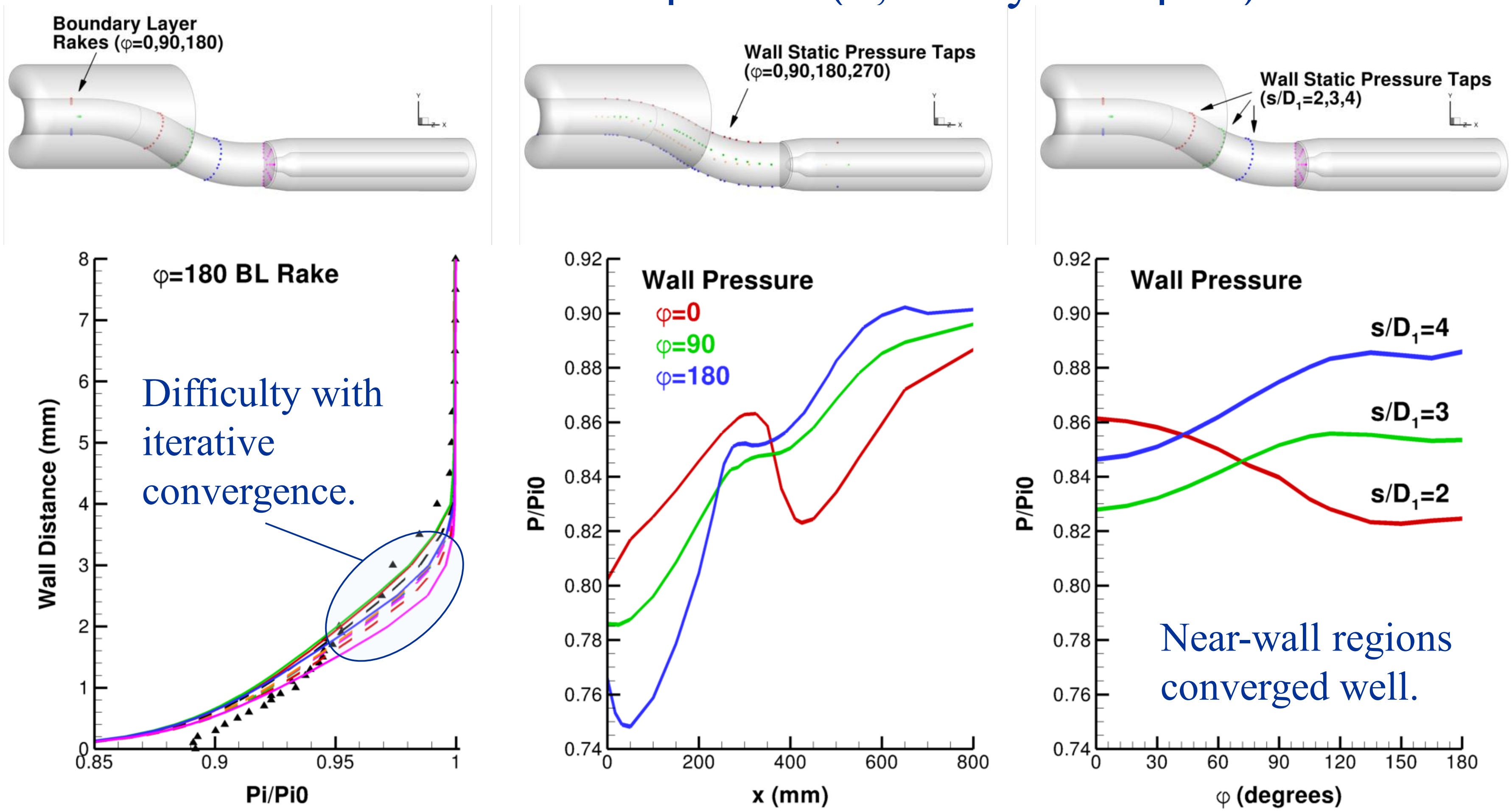
Solution Convergence

Medium Grid, SST

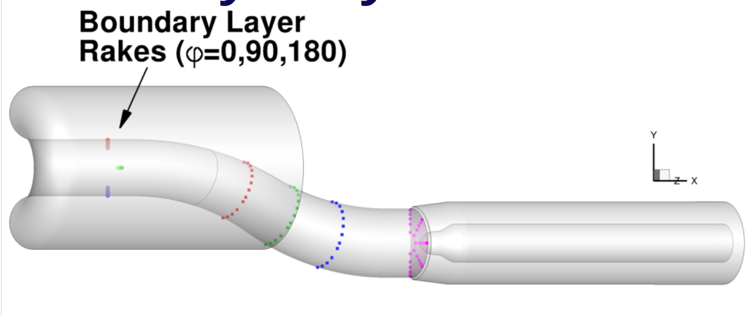


Solution Convergence

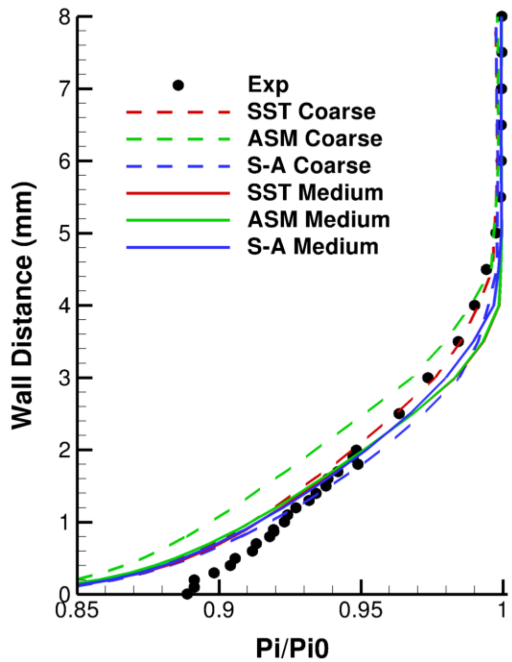
Medium Grid, SST
Last 10 solutions plotted (1,000 cycles apart).



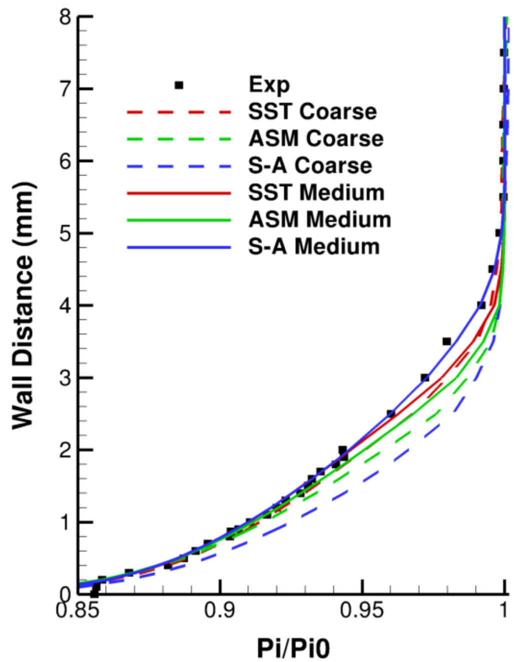
Boundary Layer Rake Data



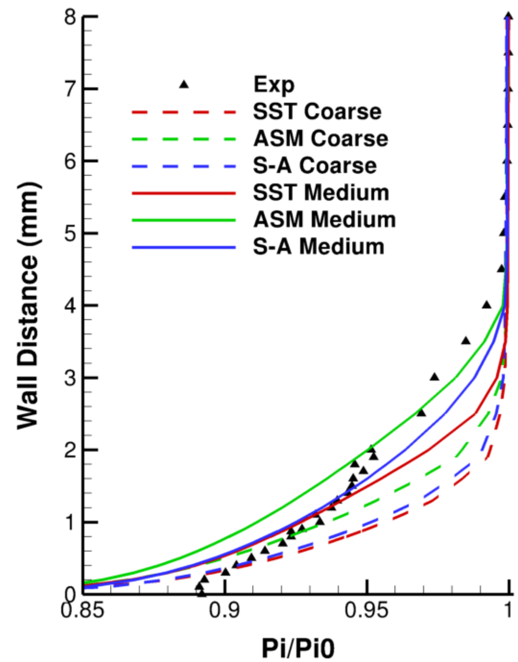
$\Phi=0°$



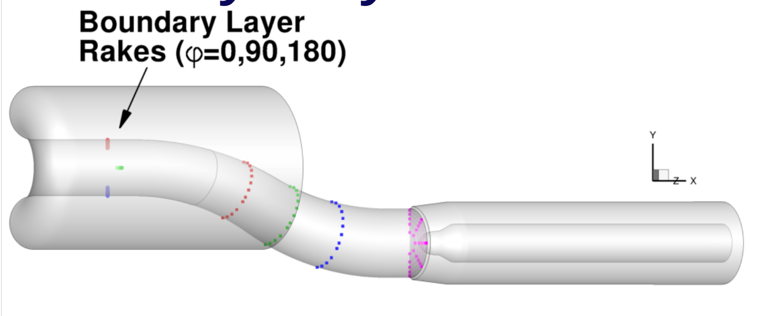
$\Phi=90°$



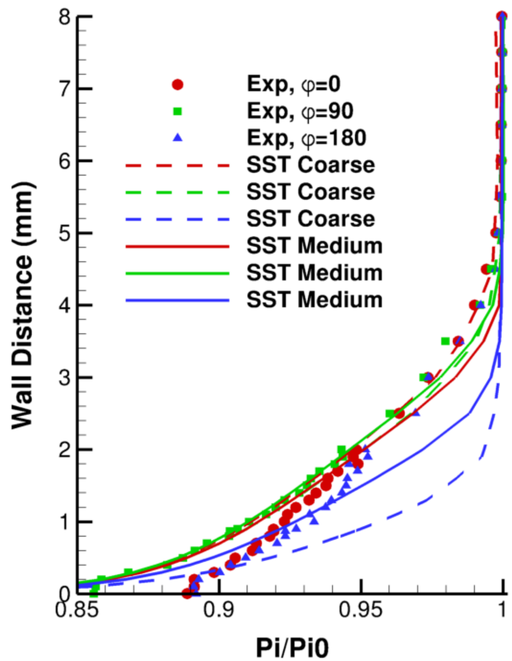
$\Phi=180°$



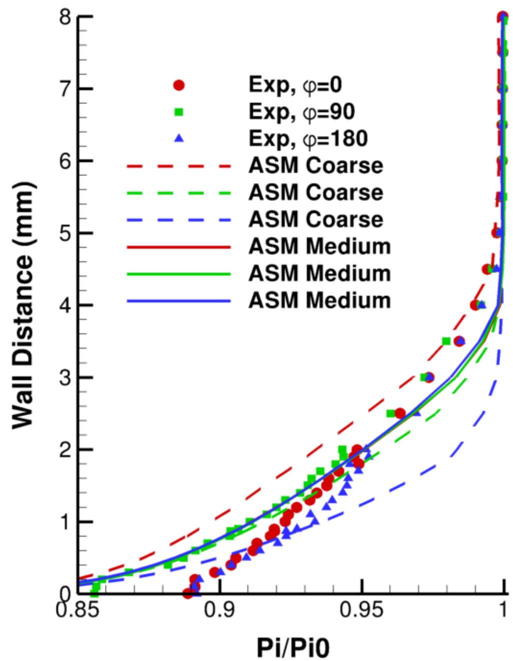
Boundary Layer Rake Data



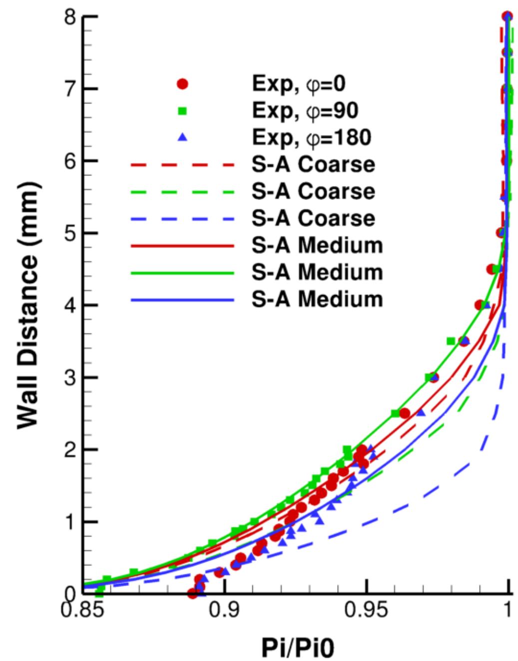
SST



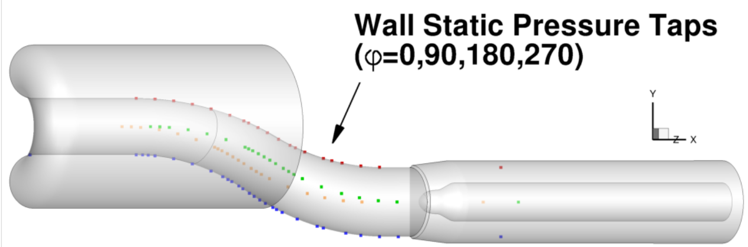
ASM k-ε



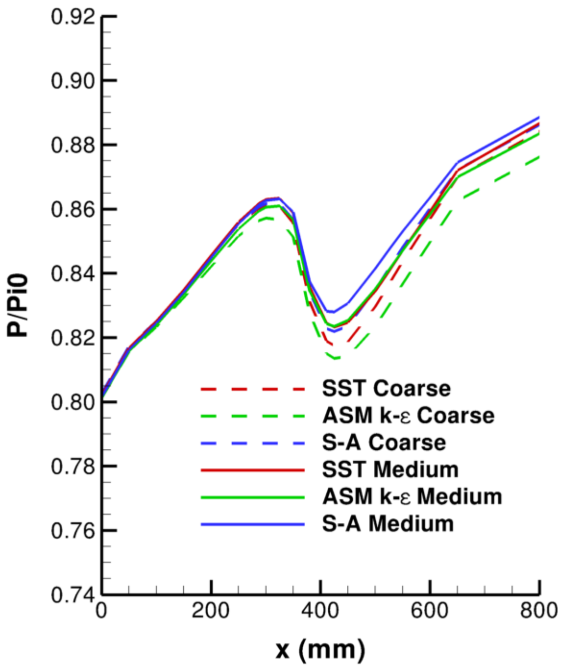
Spalart



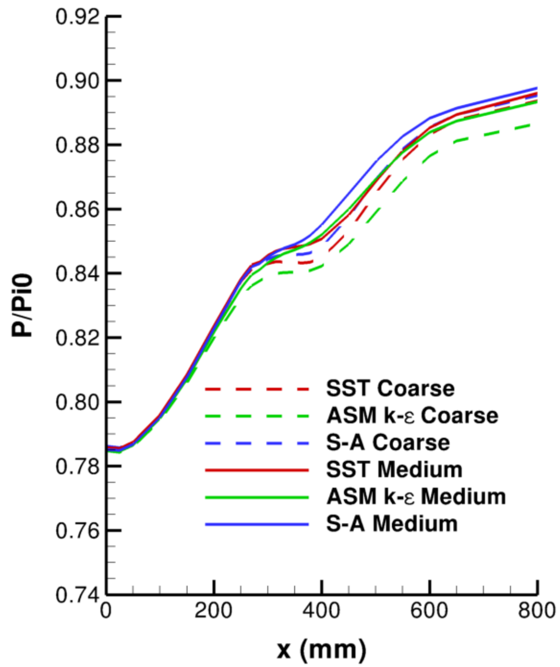
Streamwise Pressure Variation



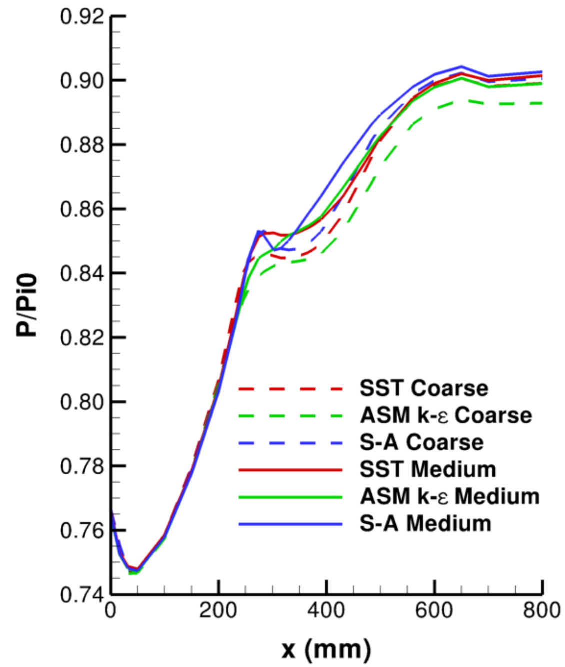
Φ=0°



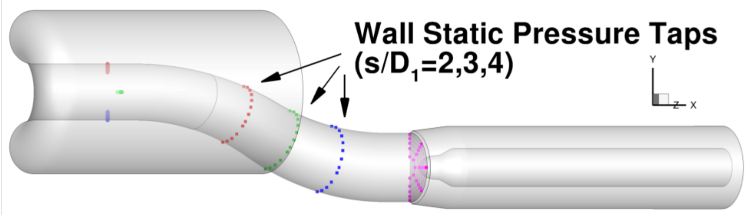
Φ=90°



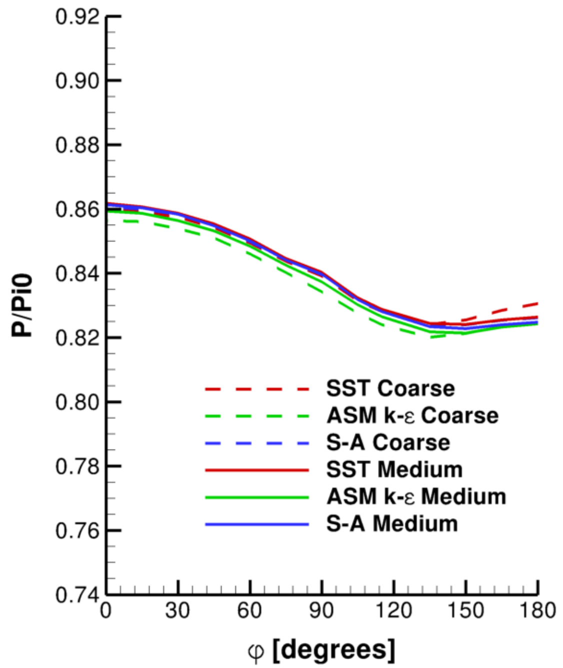
Φ=180°



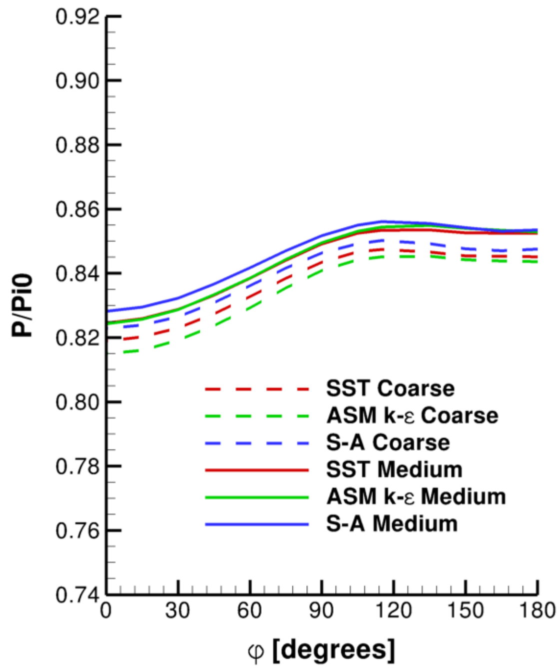
Circumferential Pressure Variation



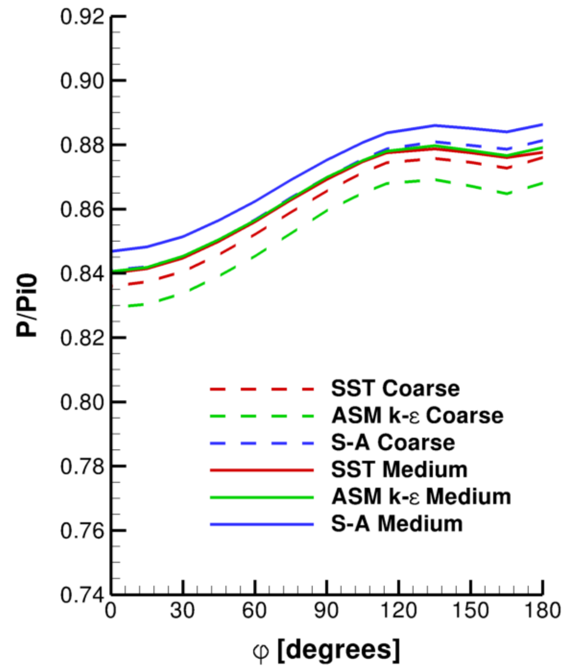
$s/D_1=2$



$s/D_1=3$



$s/D_1=4$

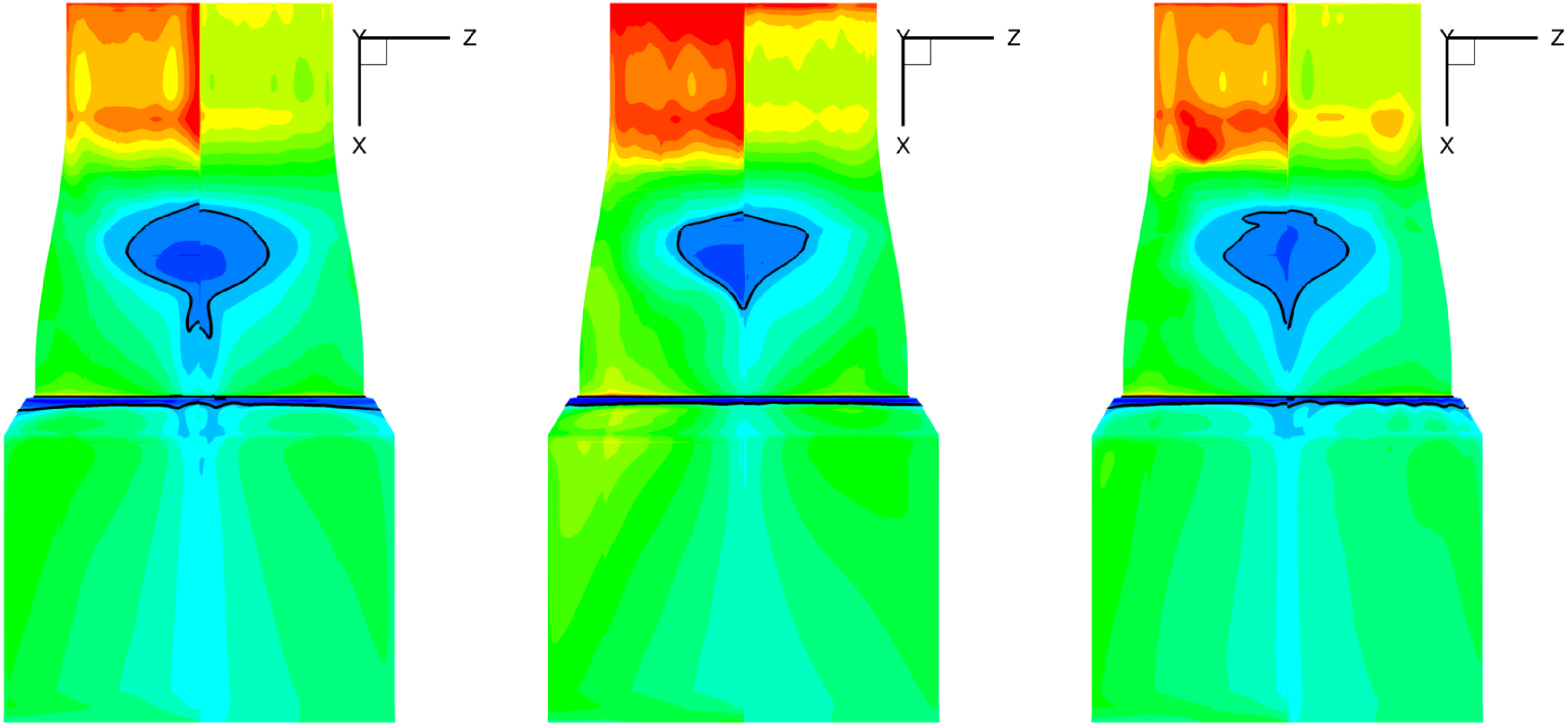


Surface Skin Friction & Flow Separation

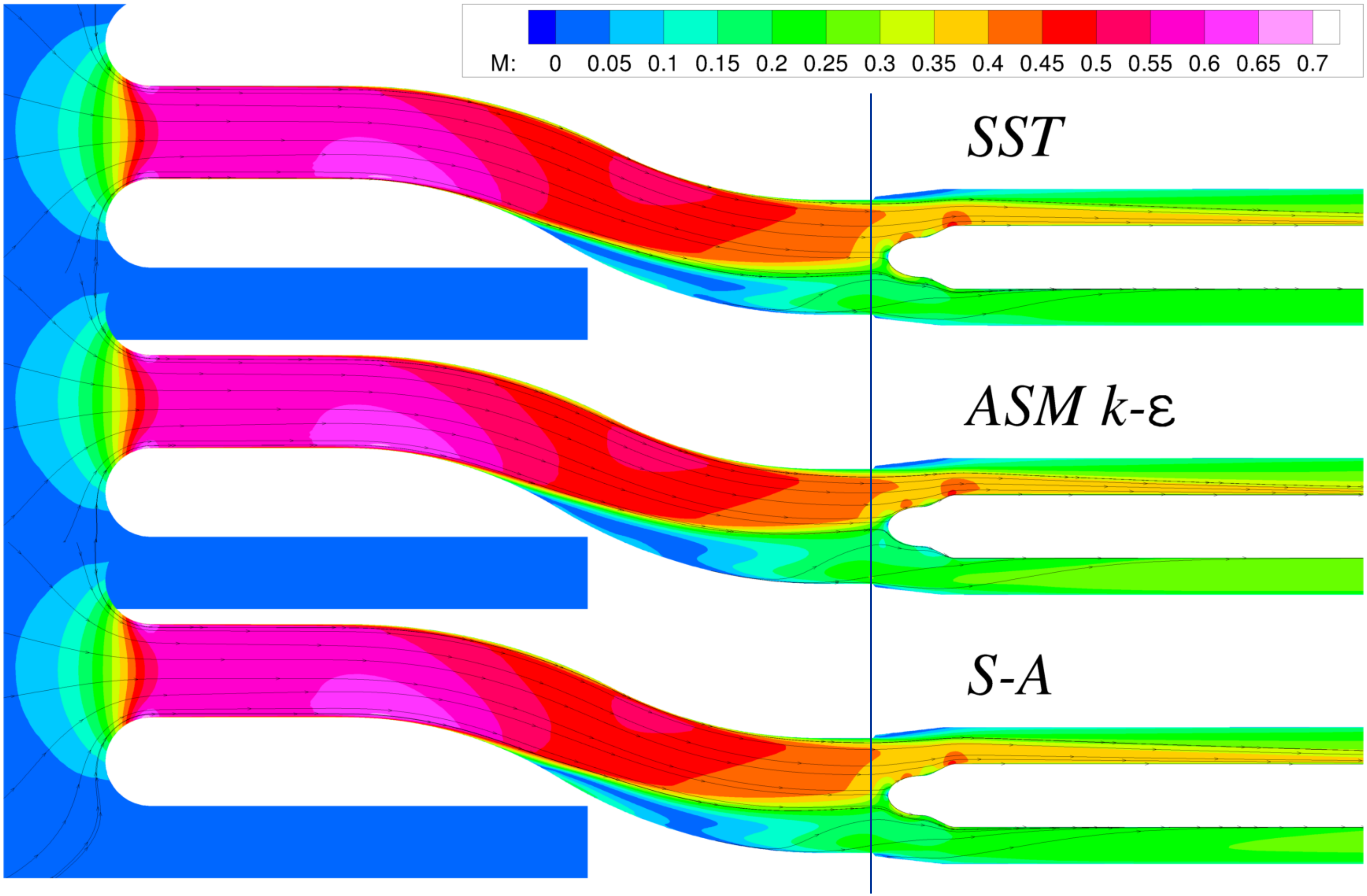
SST — Coarse, Medium

ASM k-ε — Coarse, Medium

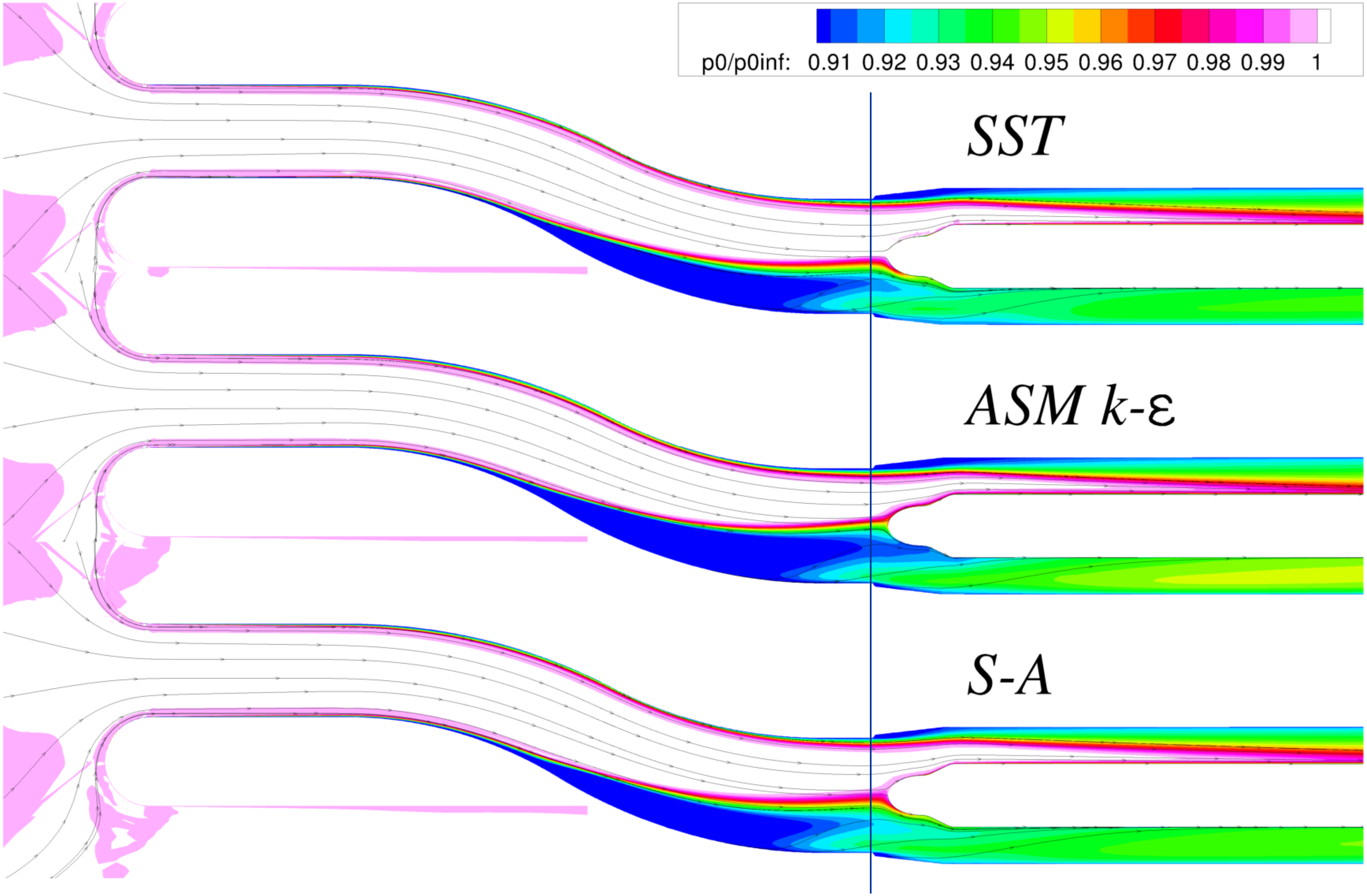
S-A — Coarse, Medium



Symmetry Plane – Medium Grid



Symmetry Plane – Medium Grid



AIP Virtual Total Pressure Rake