

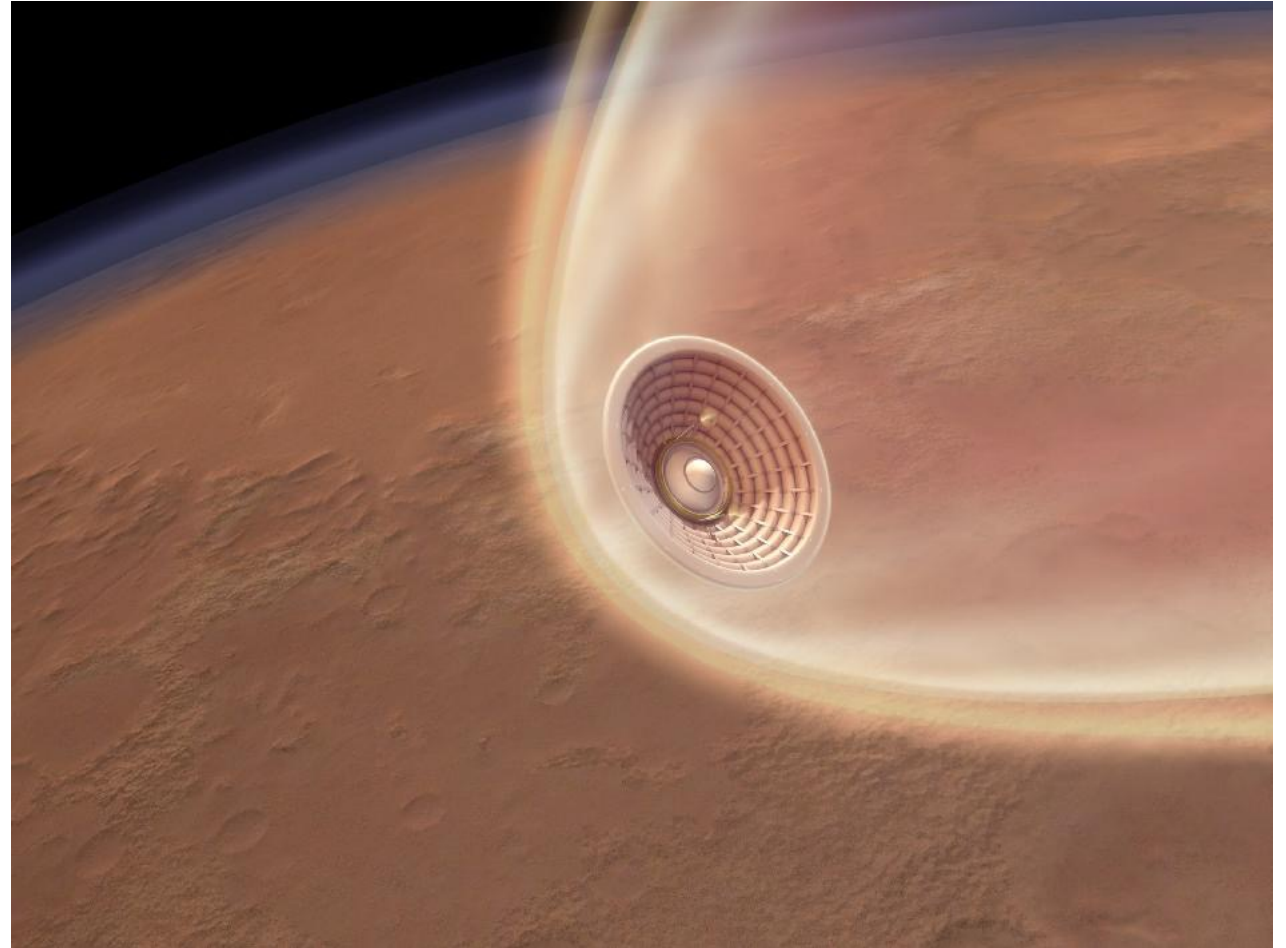
Aeroheating Predictions for a Hypersonic, Turbulent Near-Wake

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- While heatshields experience the highest heating rates, future missions will require more accurate wake heating.
- Hypersonic inflatable decelerators are an enabling new technology. They also introduce new challenges when designing thermal protection systems (TPS).
 - Backshell has convex portions.
 - The payload and the straps have minimal TPS.
- Accurately predicting heating is essential to the design of thermal protection systems and mission success.



Artist rendering of a Hypersonic Inflatable Aerodynamic Decelerator (HIAD) during Mars entry [Source: NASA].

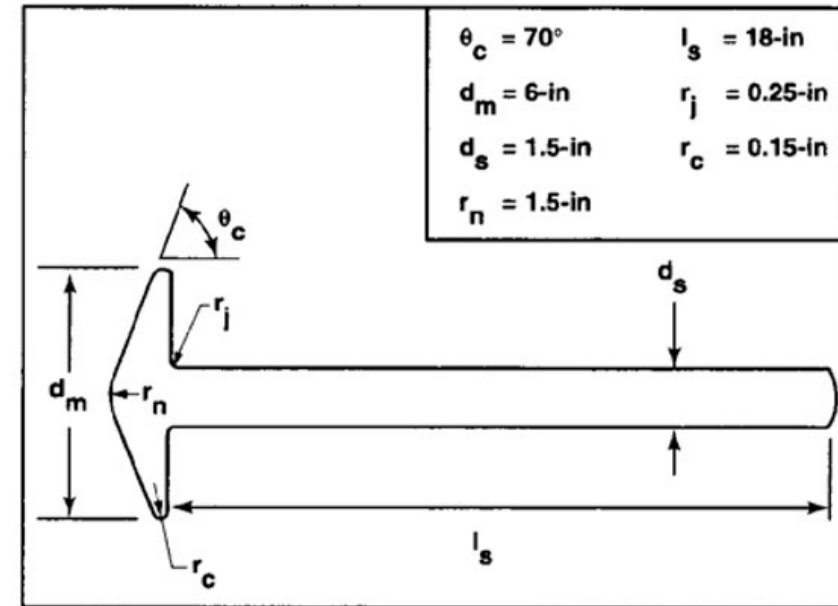
Problems

- Many previous validation studies show results for a single grid or a single Reynolds number.
- Comparisons between SST and hybrid RANS/LES are infrequent in the hypersonic wake-flow literature.

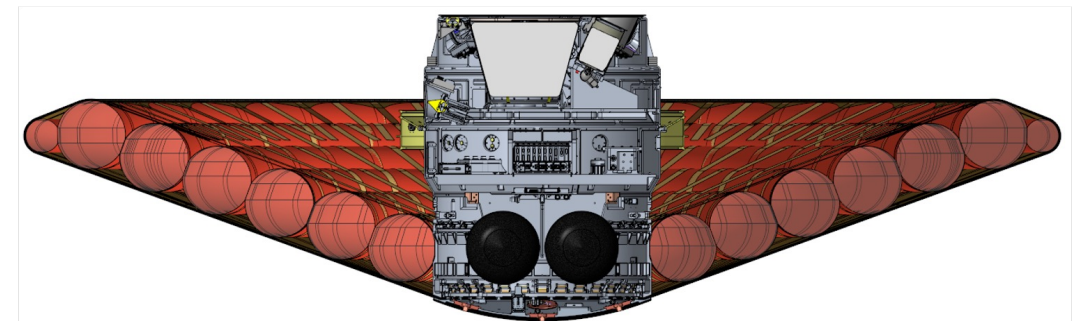
Questions

- What level of fidelity do steady RANS models provide?
 - They have limited accuracy in separated regions, but is the accuracy sufficient for engineering decisions?
- Can these aeroheating predictions be reproduced:
 - With different solvers?
 - With different meshes?
- Can hybrid RANS/LES provide improved accuracy?

- Between 1994 and 1998, the NATO AGARD organized Working Group 18 to study “Hypersonic Experimental and Computational Capability, Improvement and Validation”
- One sub-task was examining wake flows using a common research model.
- The forebody was a 70-degree sphere-cone, like the previous Viking and Pathfinder missions.
- The sting was instrumented to measure heat transfer in the wake
- There are many geometric similarities between the AGARD WG18 geometry and the LOFTID geometry.



Schematic of the AGARD WG-18 geometry



Cross-section of the LOFTID vehicle.

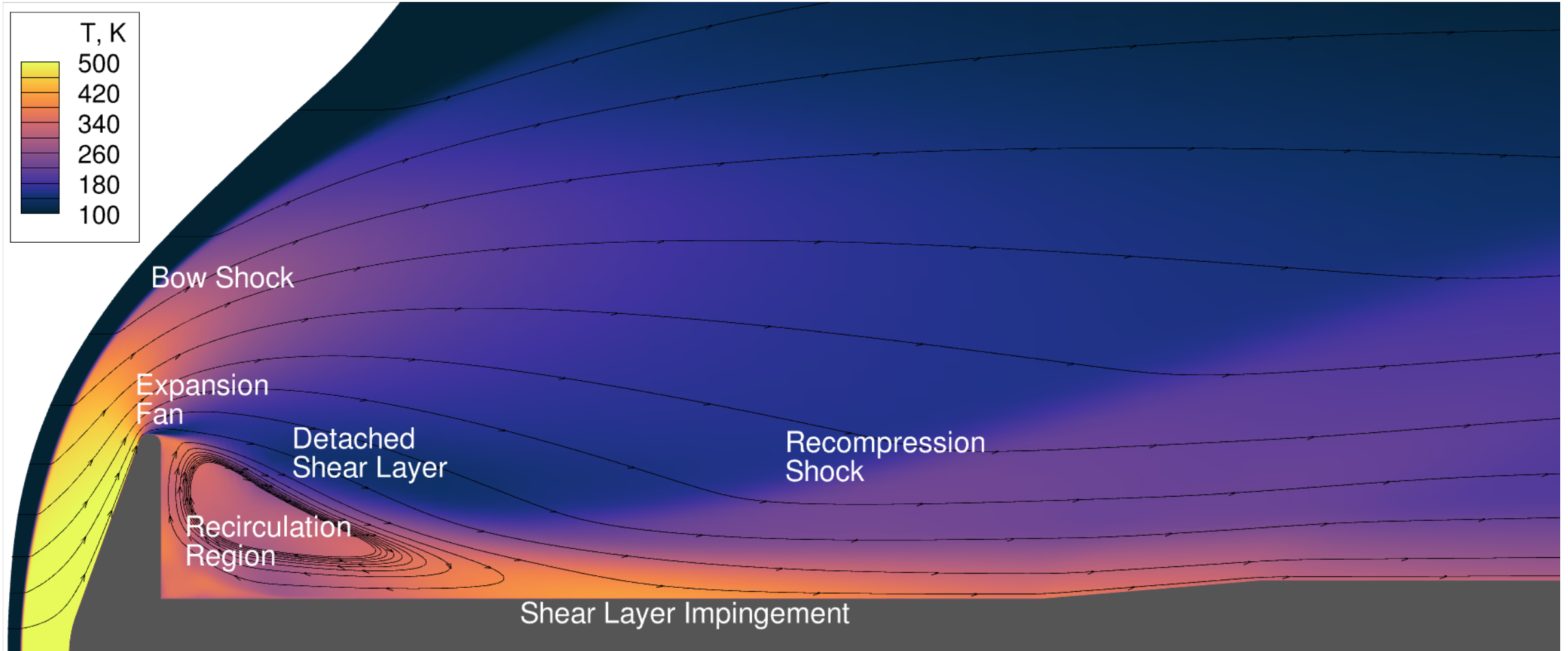
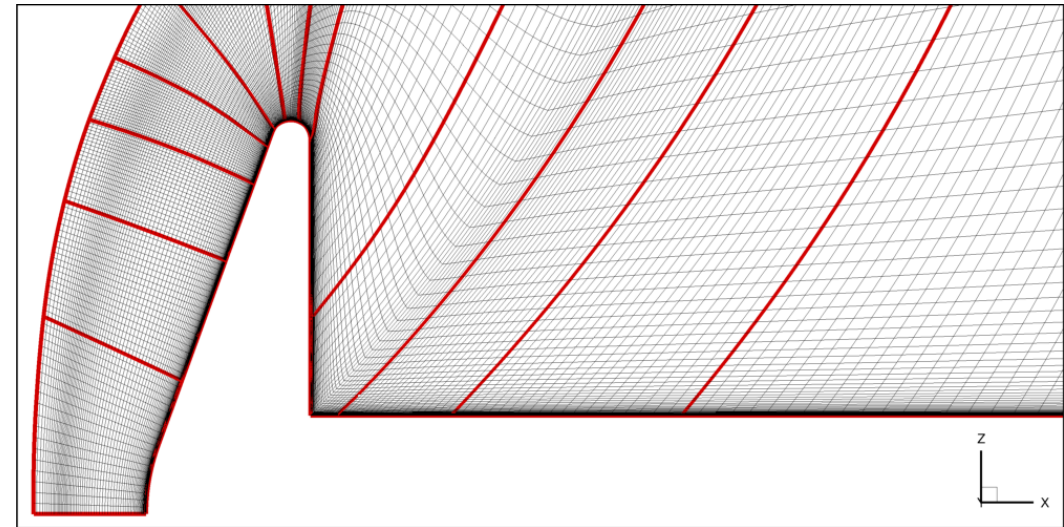


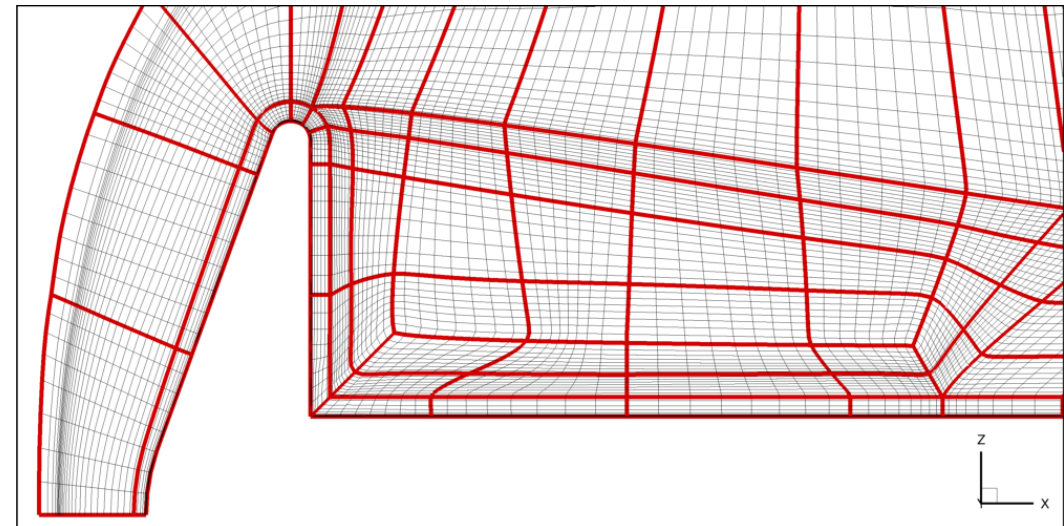
Illustration of the flow features for the wake of the AGARD WG-18 geometry. Conditions are Mach 6 and $Re_D = 3.6 \times 10^6$

Computational Setup

- Three finite-volume CFD codes:
 1. LAURA
 2. FUN3D
 3. HyperSolve
- Various grid types:
 - Conventional, axisymmetric structured meshes with continuous lines from body to farfield
 - “Stacked-block” axisymmetric meshes
 - Unstructured 3D meshes. These meshes are adapted using multiscale metric adaptation



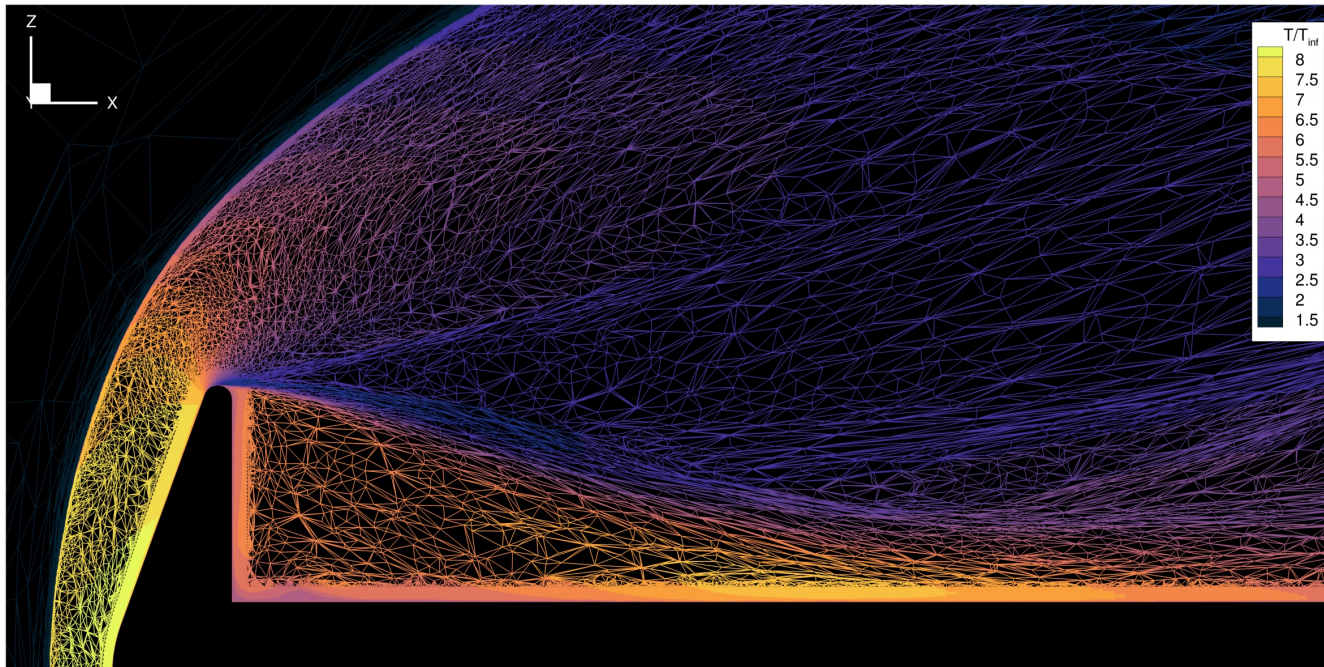
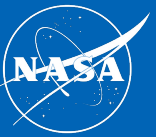
Conventional structured mesh



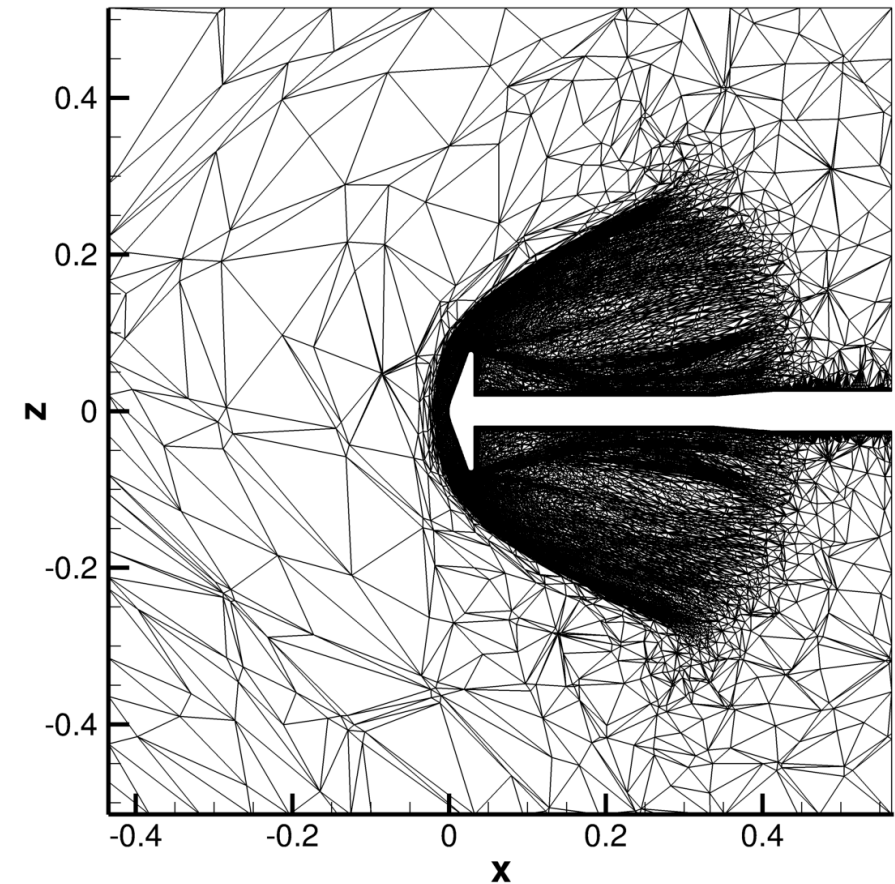
Stacked-block mesh

[1] Yee, H. et al. “Entropy Splitting and Numerical Dissipation,” JCP 2000
 [2] Edwards, J., “Towards Unified CFD Simulations of Real Fluid Flows,” 2001
 [3] Nishikawa, H. et al. “Effects of High-Frequency Damping on Iterative Convergence of an Implicit Viscous Solver,” JCP 2017.

Unstructured, Adapted Meshes

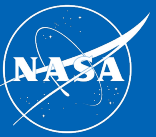


Slice through the symmetry plane of the unstructured mesh, colored with contours of the nondimensional temperature.



Slice of the unstructured mesh, showing the outer boundaries.

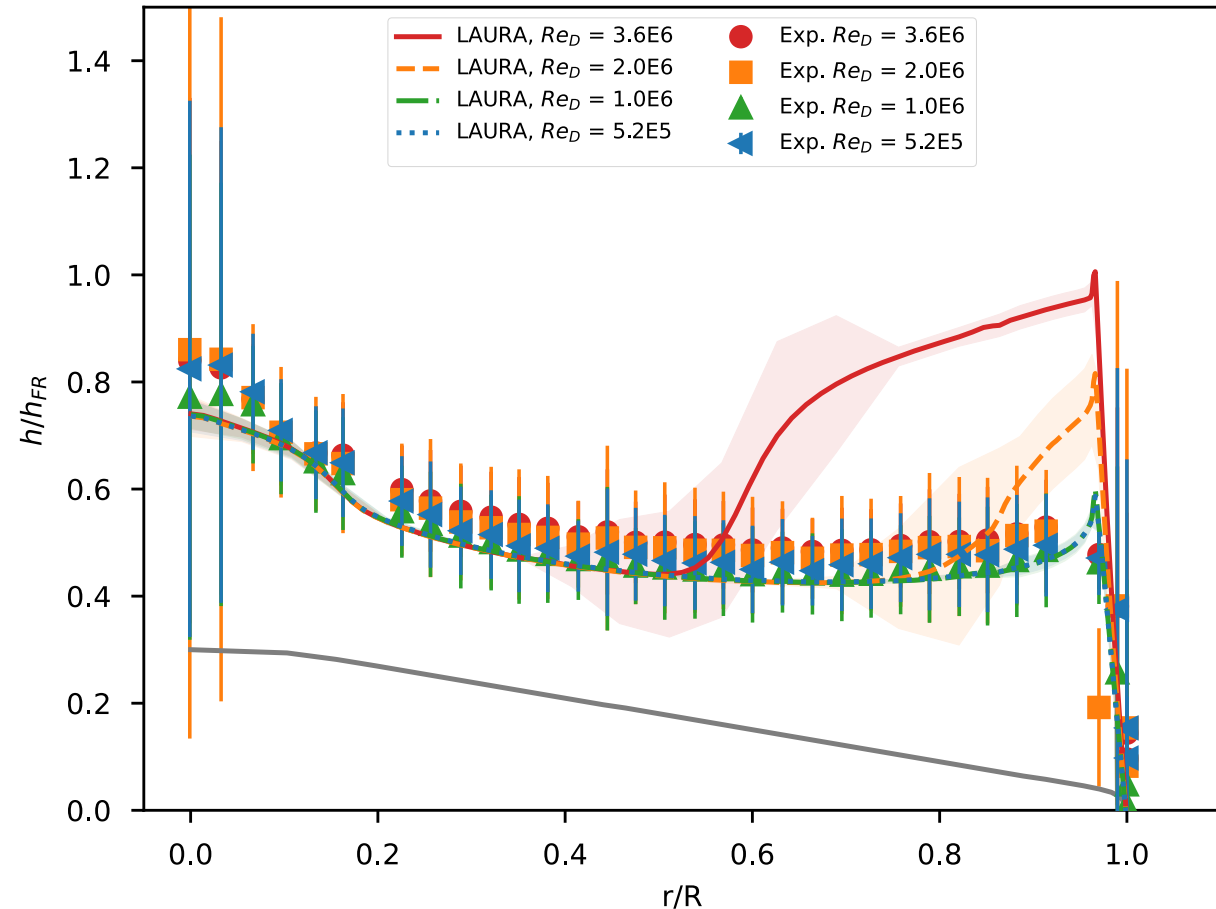
Reynolds Number Sweep: Forebody



- Experimental data is reported using a heat transfer coefficient:

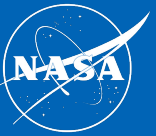
$$h \equiv q_w / (H_\infty - H_w)$$

- This value is normalized by the heat transfer coefficient predicted by Fay-Riddell theory.
- SST results predict the laminar region of the forebody well but predict too early a transition.

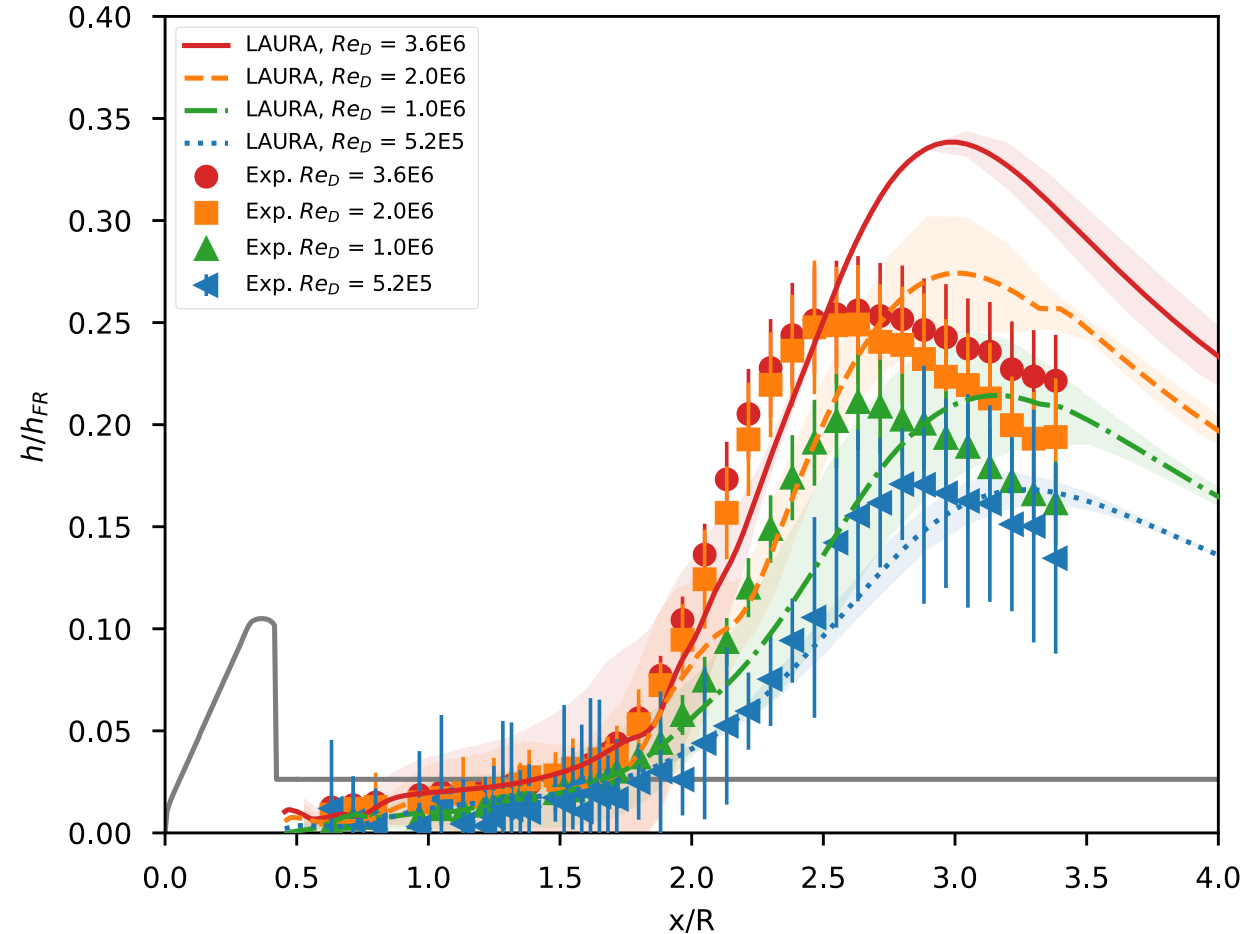


Comparison of experimental data and LAURA predictions for a range of Reynolds numbers. Shaded regions show the estimated discretization error. The geometry is shown in gray at the bottom.

Reynolds Number Sweep: Wake

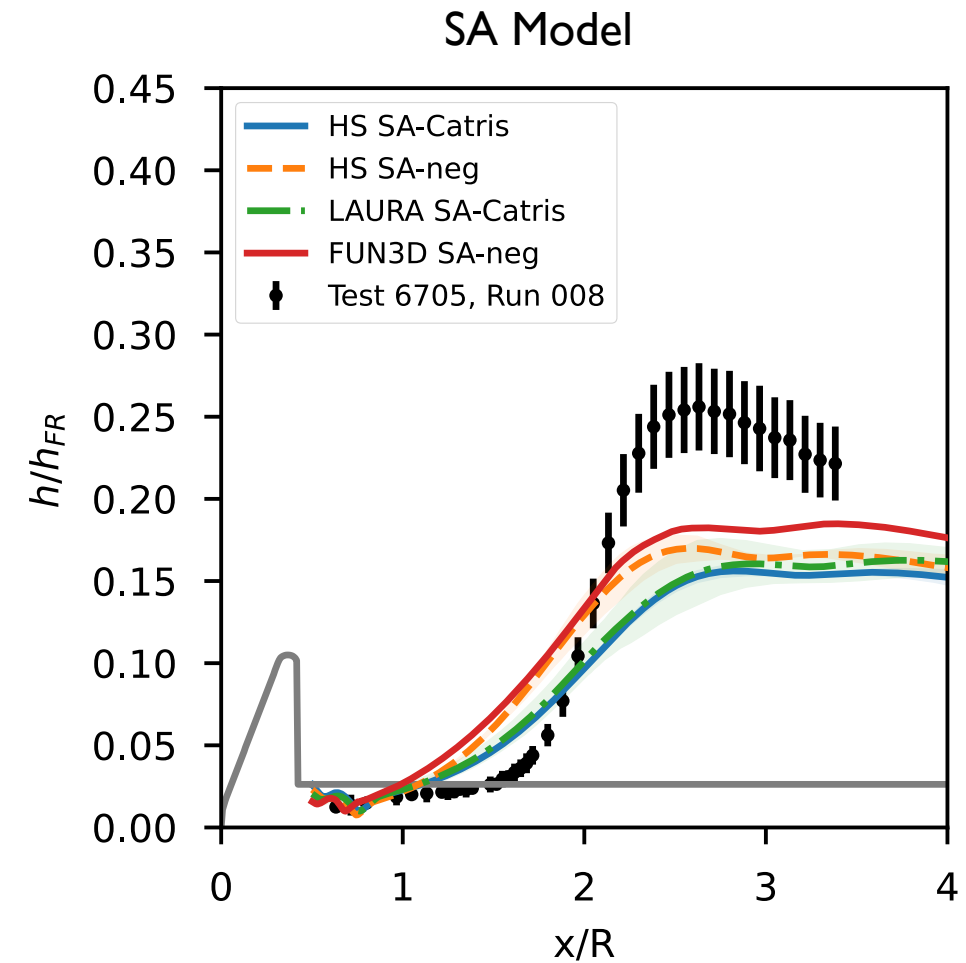
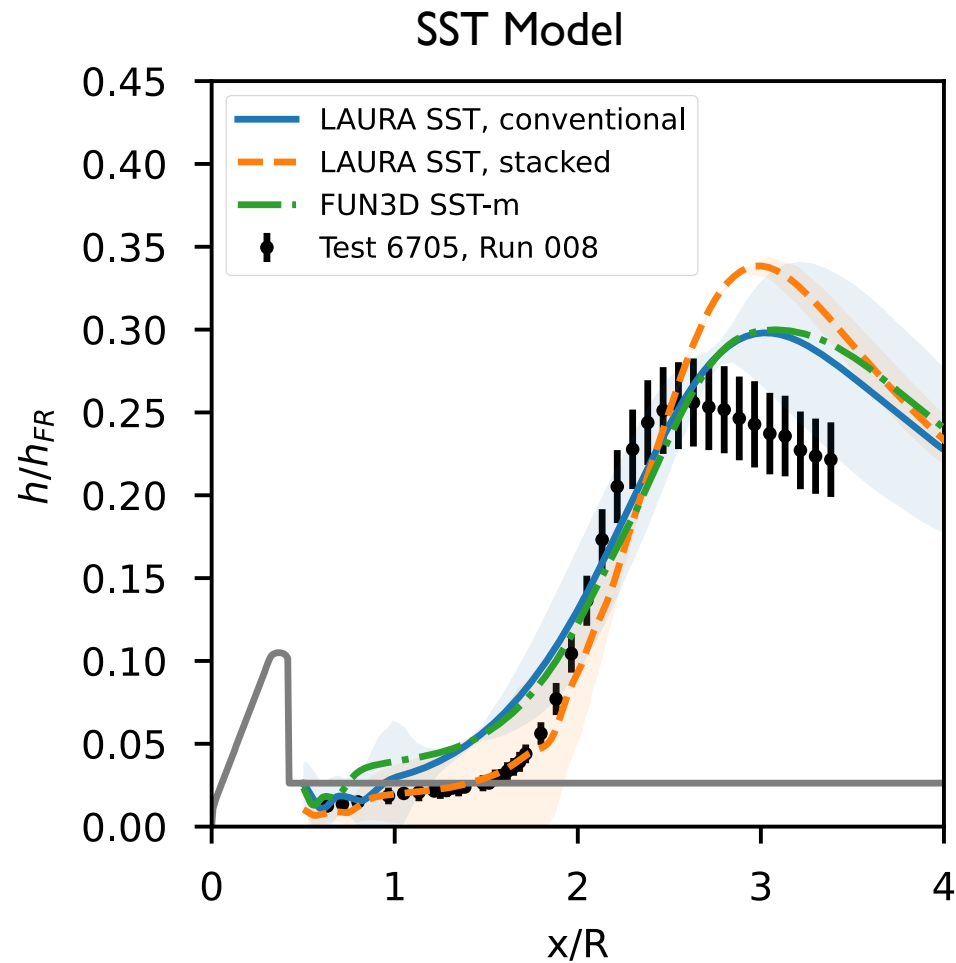
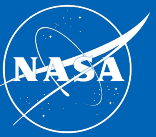


- CFD predicts smooth increase in peak heating with increases in Reynolds number
- Experimental data shows a much smaller difference between $Re=2.0E6$ and $Re=3.6E6$ (the two highest Reynolds numbers)
- Peak occurs too far downstream, and the rise is too gradual.



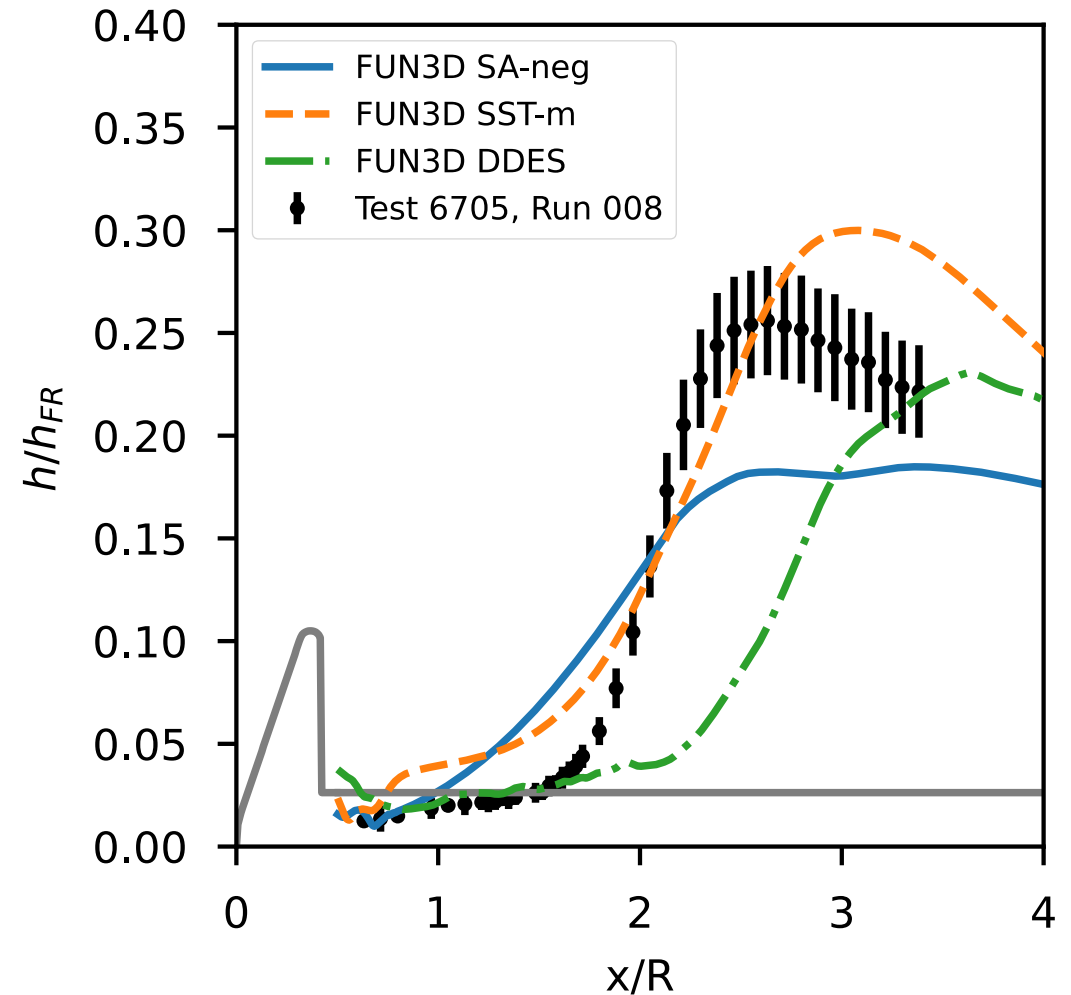
Comparison of experimental data and LAURA predictions for a range of Reynolds numbers. Shaded regions show the estimated discretization error. The geometry is shown in grey at the bottom.

Consistency Across Solvers



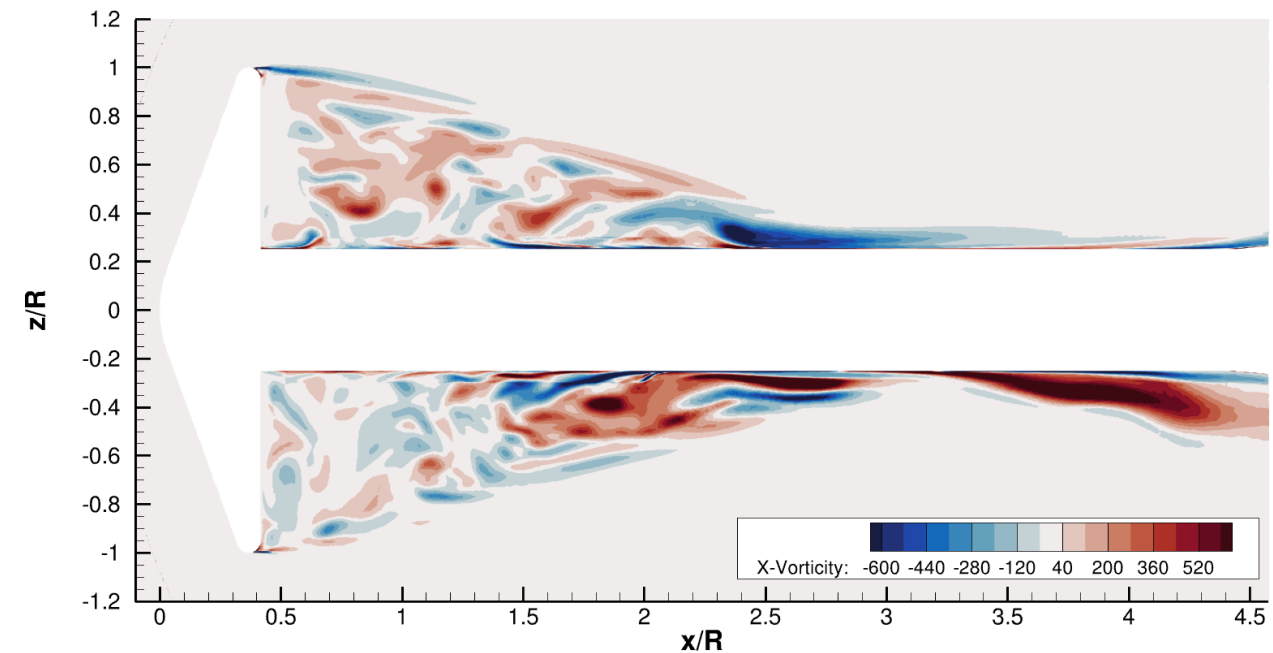
Comparison of experimental data and LAURA predictions for Mach 6 and $Re_D = 3.6 \times 10^6$. Shaded regions show the estimated discretization error. The geometry is shown in gray at the bottom.

- The highest Reynolds number case was also tested with DDES, a hybrid RANS/LES model.
- The initial RANS grid was modified to add finer, isotropic cells in the separated flow region.
- DDES uses SA-neg as the underlying RANS model.
- DDES gives an improved prediction of peak heating, but the peak occurs too far downstream.



Why does DDES not perform better?

- The sting / reattachment region has very different physics than a clean wake region.
- Resolution of $\Delta/D \approx 0.007$ with second-order numerics is sufficient only to resolve the largest scales; smaller scales are absent.
 - Adding local refinement around this region makes results worse due to modeled stress depletion.
- More research should be conducted on hybrid RANS/LES models that are robust to under-resolved grids or changes in grid resolution.



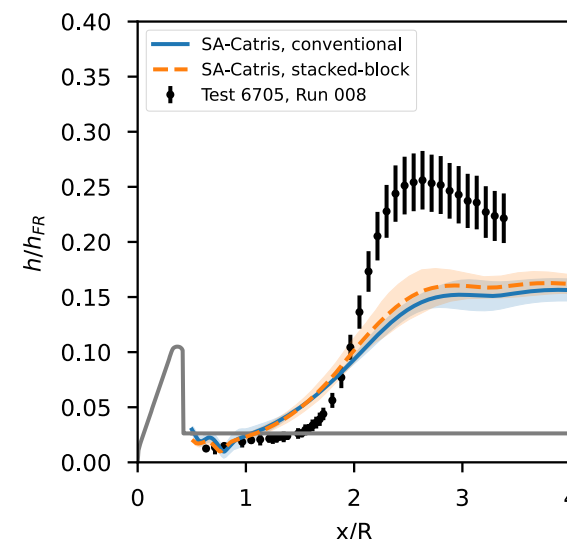
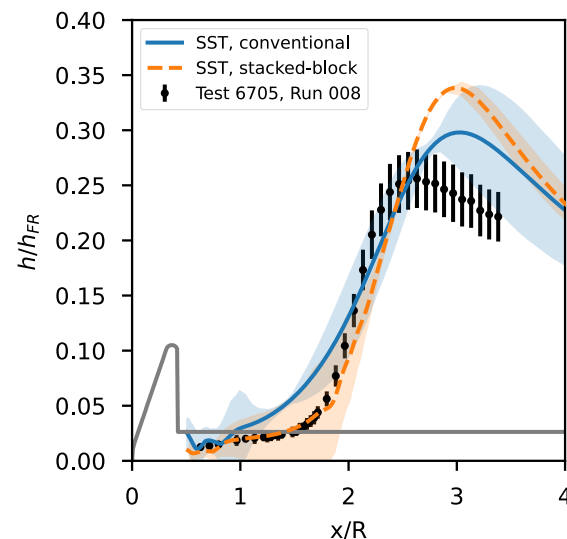
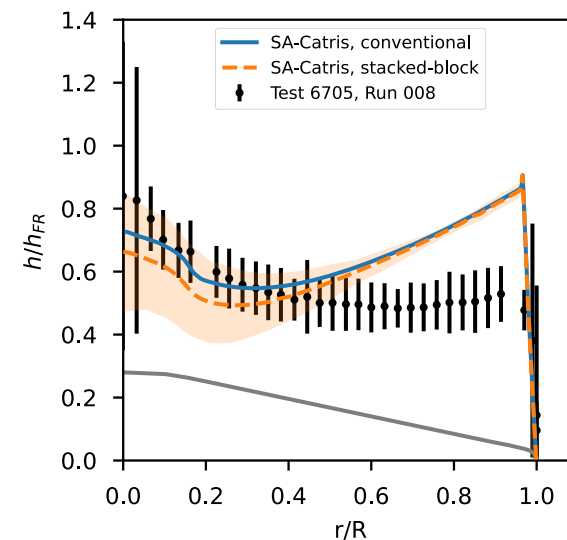
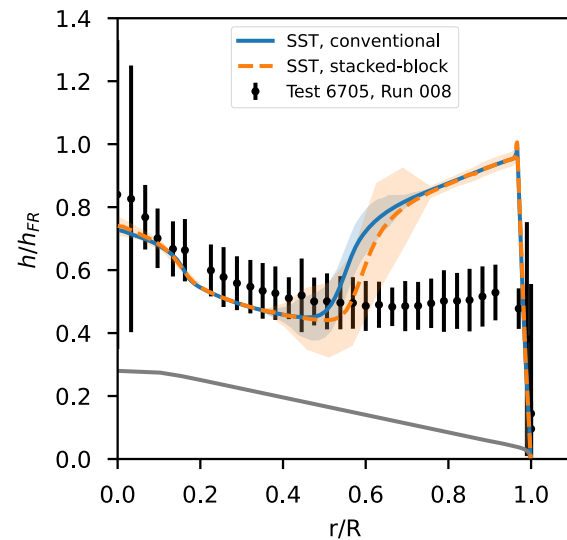
Instantaneous snapshot of the vorticity in the x-direction. Conditions are Mach 6 and $Re_D = 3.6 \times 10^6$

- Wake heating was validated using various mesh topologies and various turbulence models.
- Results are generally consistent across meshes and solvers once discretization error is included.
- SST models predict peak heating to within 20%
 - The predicted rise is too gradual; experimental data rises more quickly
- SA models underpredict wake heating due to too much eddy viscosity
 - SA-Catris performs *worse* than standard SA models in the wake flow region.
- DES improves on the peak heating magnitude, but peak location is too far downstream

Backup Slides

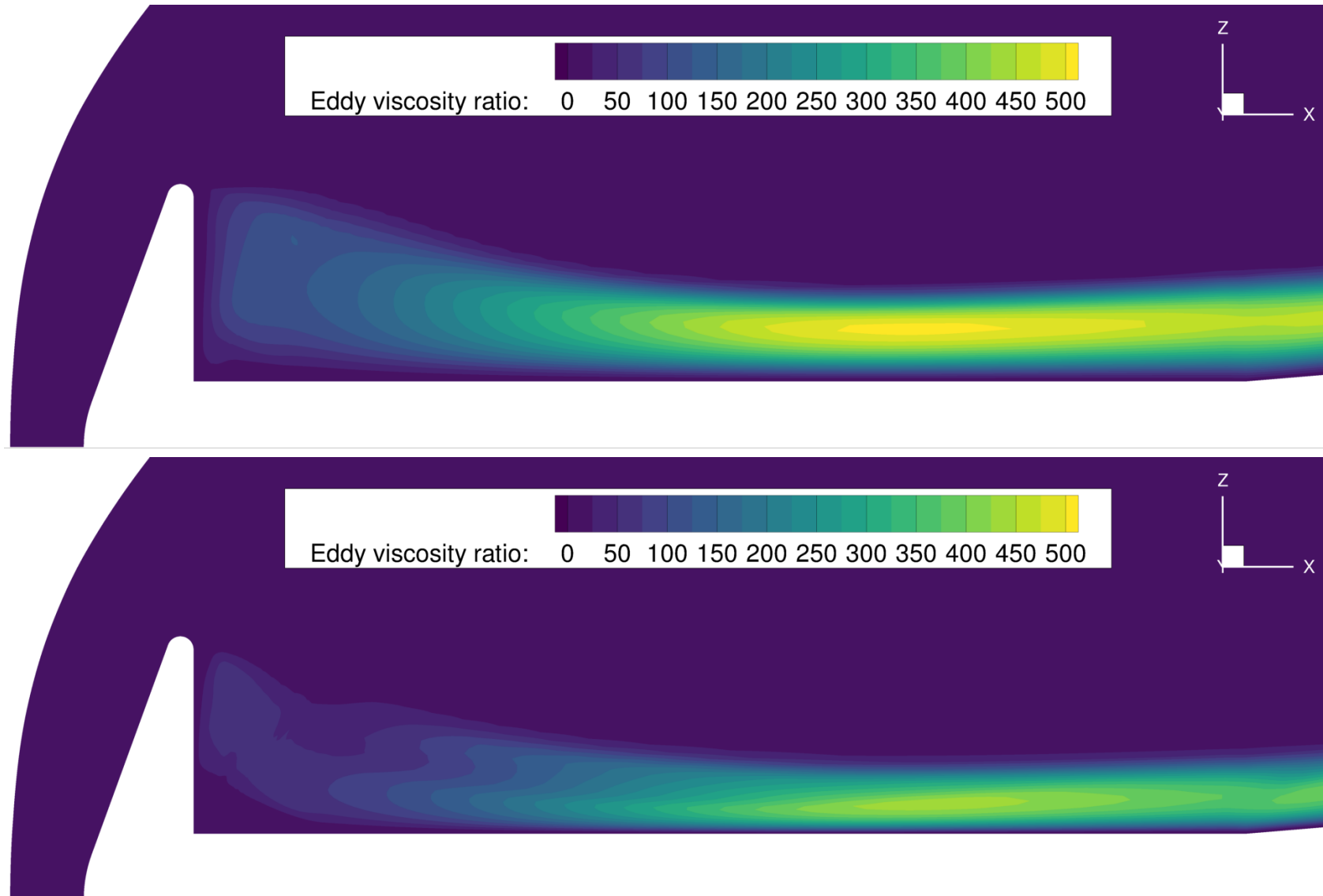
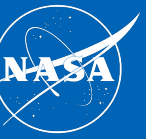
Consistency Across Mesh Topologies

- Generally, the results seem to be consistent across mesh topologies once discretization error is considered.
- There is a discrepancy between SST results in the wake:
 - This indicates that the discretization error is inaccurate.
 - May be due to first-order accuracy or poor resolution of sharp features (such as the F_1 or F_2 functions in SST)

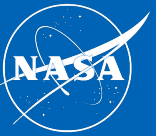


Comparison of experimental data and LAURA predictions for various grid topologies. Shaded regions show the estimated discretization error. The geometry is shown in gray at the bottom.

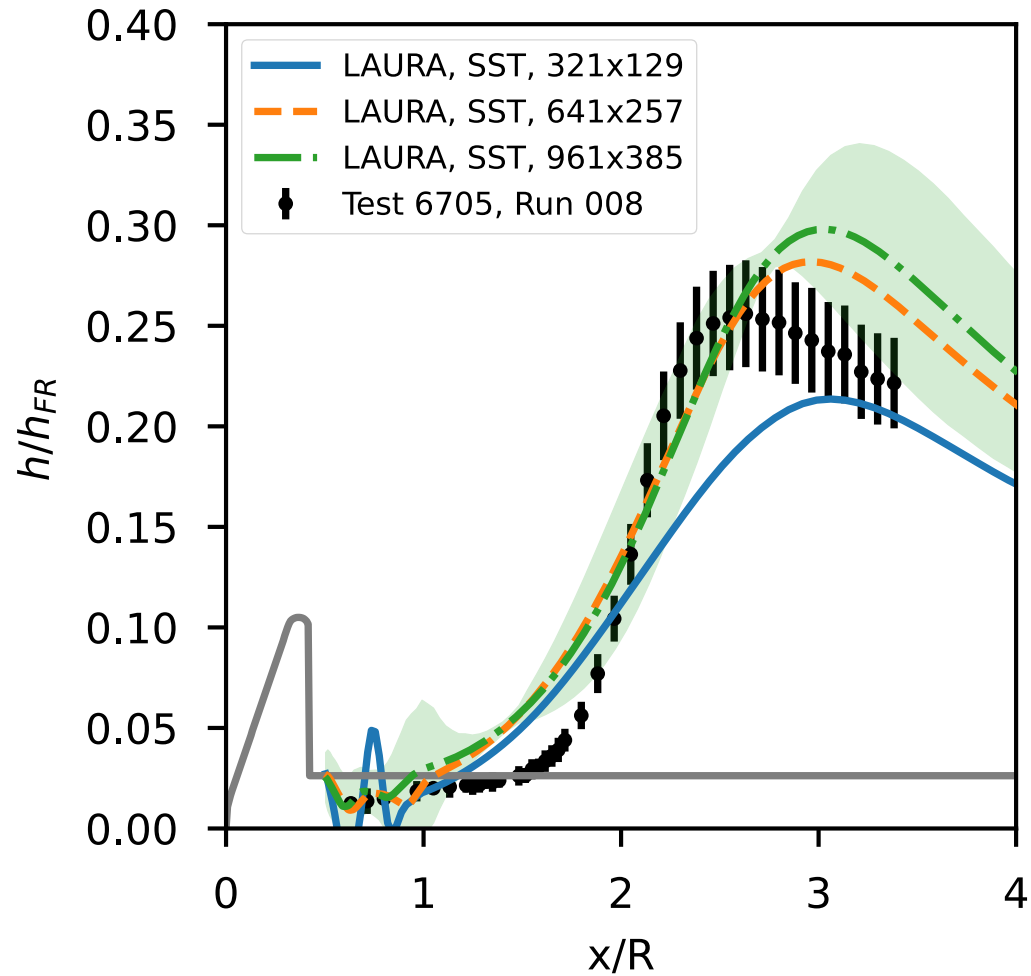
Failure of SA Models



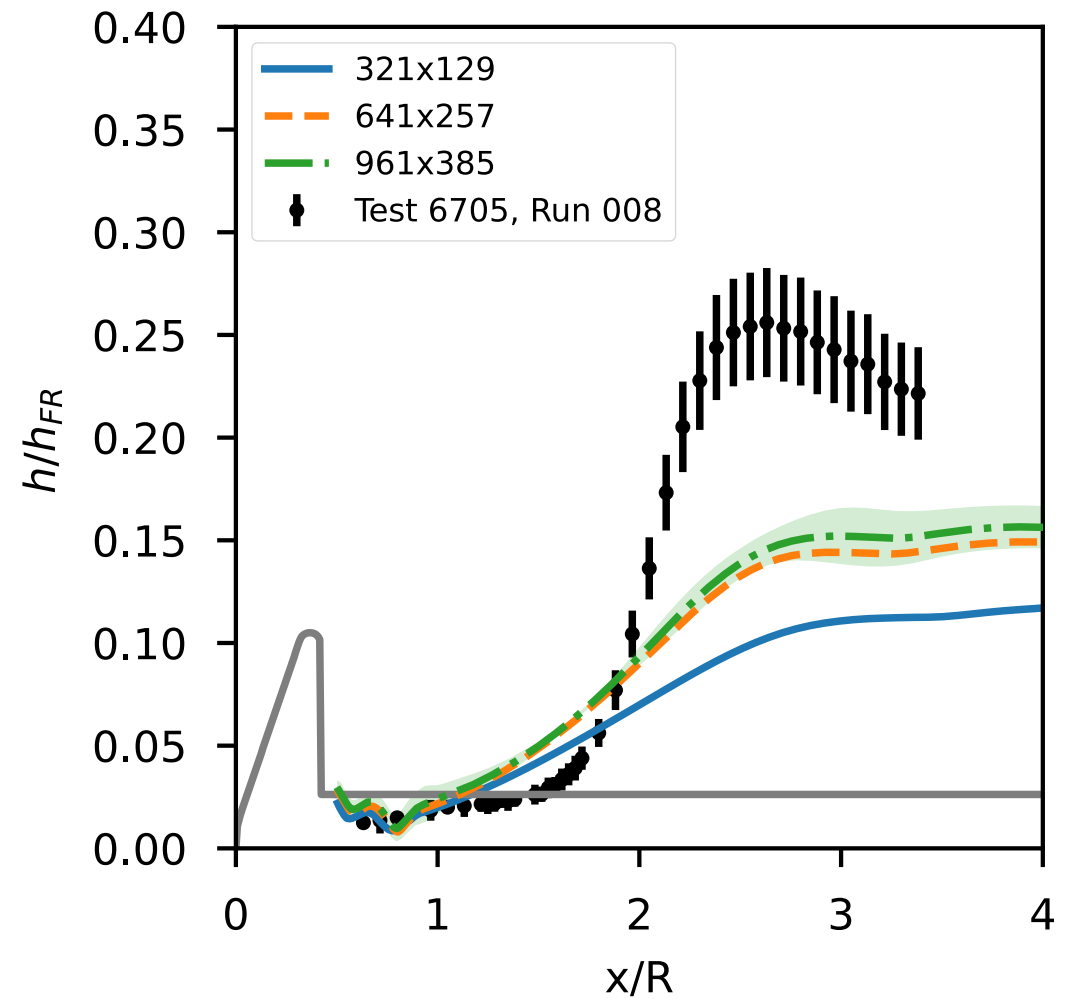
Mesh Convergence



SST Model



SA Model



DDES Mesh Refinement

