

AIAA Science and Technology Forum and Exposition,
Orlando, FL, January 6-10, 2020



Hybrid Reynolds-Averaged / Large Eddy Simulations for the NASA Enhanced Injection and Mixing Project

Robert A. Baurle and Tomasz Drozda
Hypersonic Airbreathing Propulsion Branch
NASA Langley Research Center





- **Role of CFD in Scramjet Design and Development**
 - How we use it now
 - Potential roles for scale-resolving simulations (SRS)
- **Example of using Scale-Resolved Simulations (SRS) to reduce Reynolds-Averaged Simulation (RAS) model-form uncertainty for a scramjet combustor flameholder**
 - RAS model-form uncertainty shown to be excessive
 - Calibration of RAS modeling choices via hybrid RAS/LES
- **Enhanced Injection and Mixing Project (EIMP) Flush-wall injector description**
 - Geometry and flow conditions
 - Simulation details (grid, numerical scheme, etc.)
- **Simulation results compared with measured data**
 - Computational Flow Imaging (CFI)
- **Summary**

Role of CFD in Scramjet Development



- **Current SoA for CFD analysis of hypersonic propulsion systems are Reynolds-Averaged Simulations**
 - All scales of turbulence are modeled → often leading source of uncertainty
 - Boussinesq approximation with LEVM
 - Gradient diffusion assumption with constant Pr_t and Sc_t
 - Turbulence-Chemistry interactions neglected (or crudely modeled)
 - Modeling strategy is relatively mature with only “evolutionary” improvements documented over the past 20+ years
- **Scale-Resolved Simulations have the potential to substantially reduce model-form uncertainty**
 - Only the smaller turbulence scales are modeled (larger scales resolved)
 - Larger scales responsible for “stirring” of fuel and air streams → geometry governed mixing processes are primarily resolved
 - Smaller scales more universal in nature (presumably easier to model)
 - Model form uncertainty (related to turbulence) can be reduced with grid resolution

Scale-Resolving Simulations Can Reduce Model-Form Uncertainty, but ...



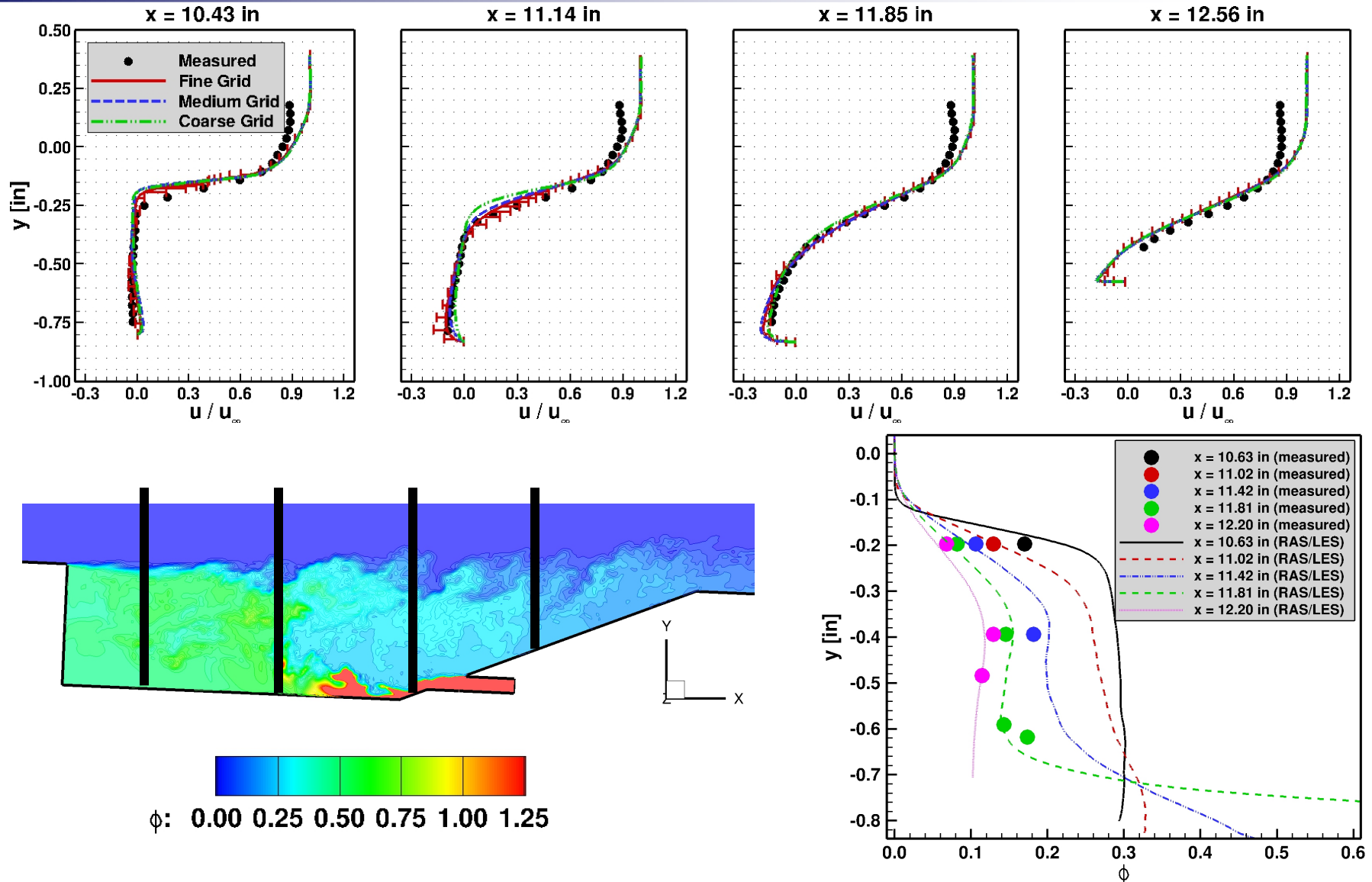
- **Cost is prohibitive**

- Given typical computer HPC resources available for engineering analysis, the time to obtain an adequately grid-resolved steady-state RAS for a full scramjet propulsion flowpath is on the order of 1 week
- Transitioning to a wall-modeled Large Eddy Simulation (LES) formulation increases this cost by a factor of at least 100
 - Nearly isotropic grid elements are required in LES regions that are a fraction of the shear layer width → 3-5 times the grid resolution of RAS
 - Temporal accuracy requires at least 5 times more work per iteration and limits the size of the time steps that can be taken
 - Statistics must be gathered after a statistically stationary state has been achieved adding at least another factor of 3 into the cost
- The bottom line is that RAS will not be replaced by scale-resolving simulations any time in the foreseeable future

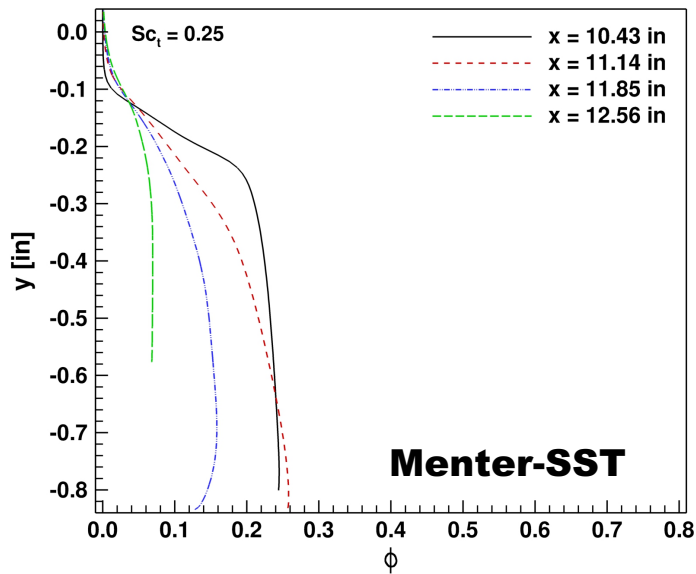
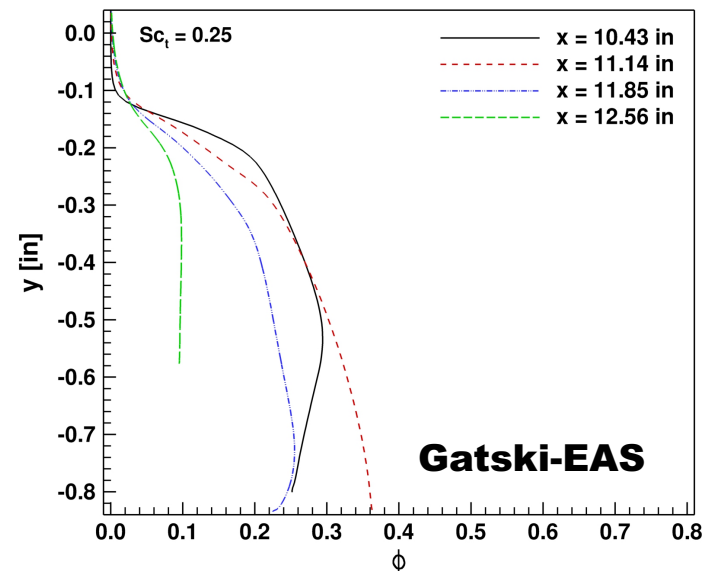
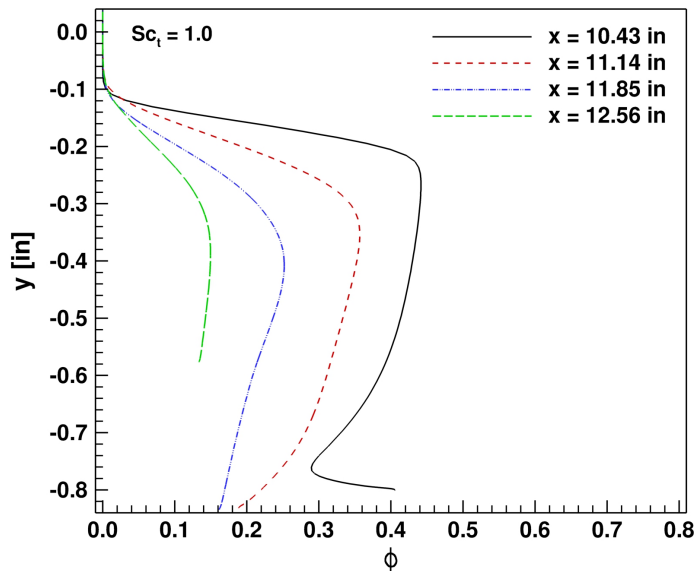
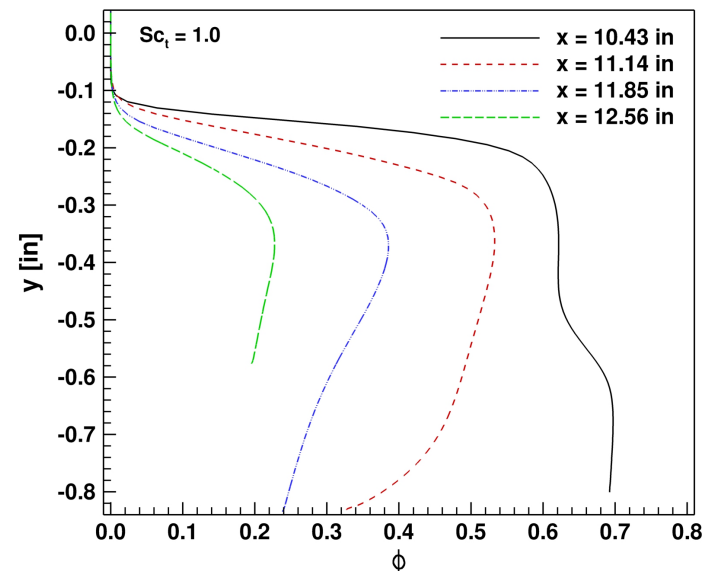
- **SRS are likely to be limited to the following scenarios:**

- Isolated key flight conditions near operability bounds
- Operating conditions where flow transients/unsteadiness are of interest
- RAS parameter model calibration to reduce model-form uncertainty

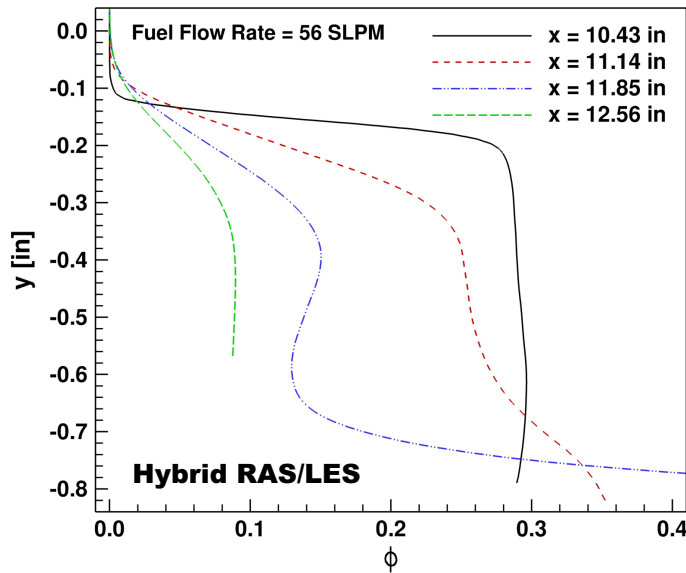
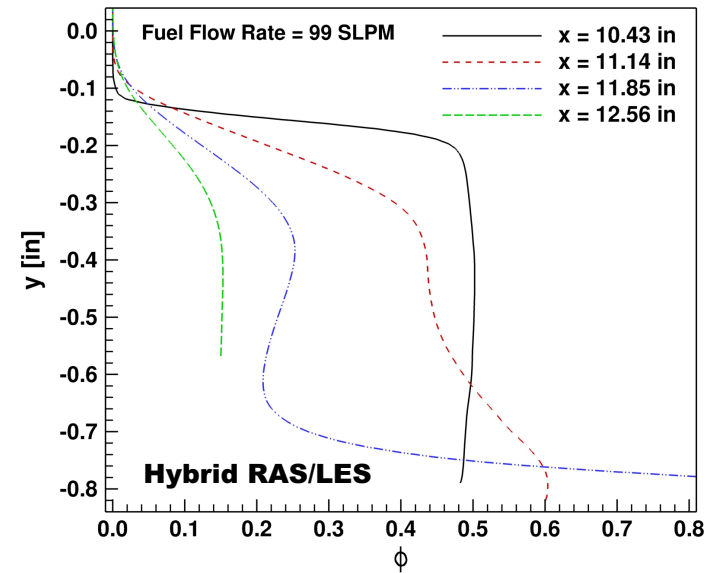
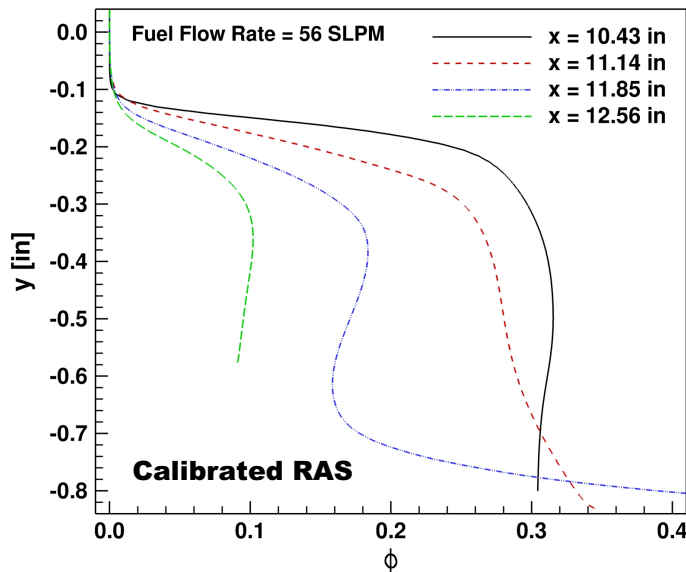
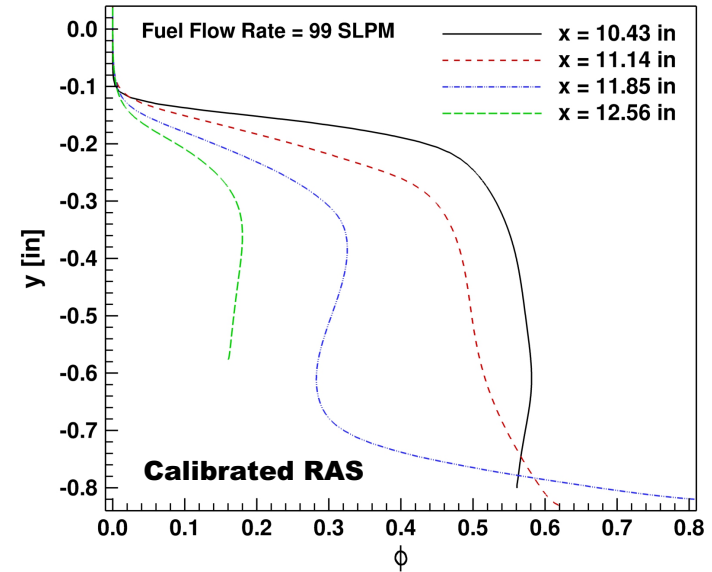
SRS of a Scramjet Combustor Flameholder



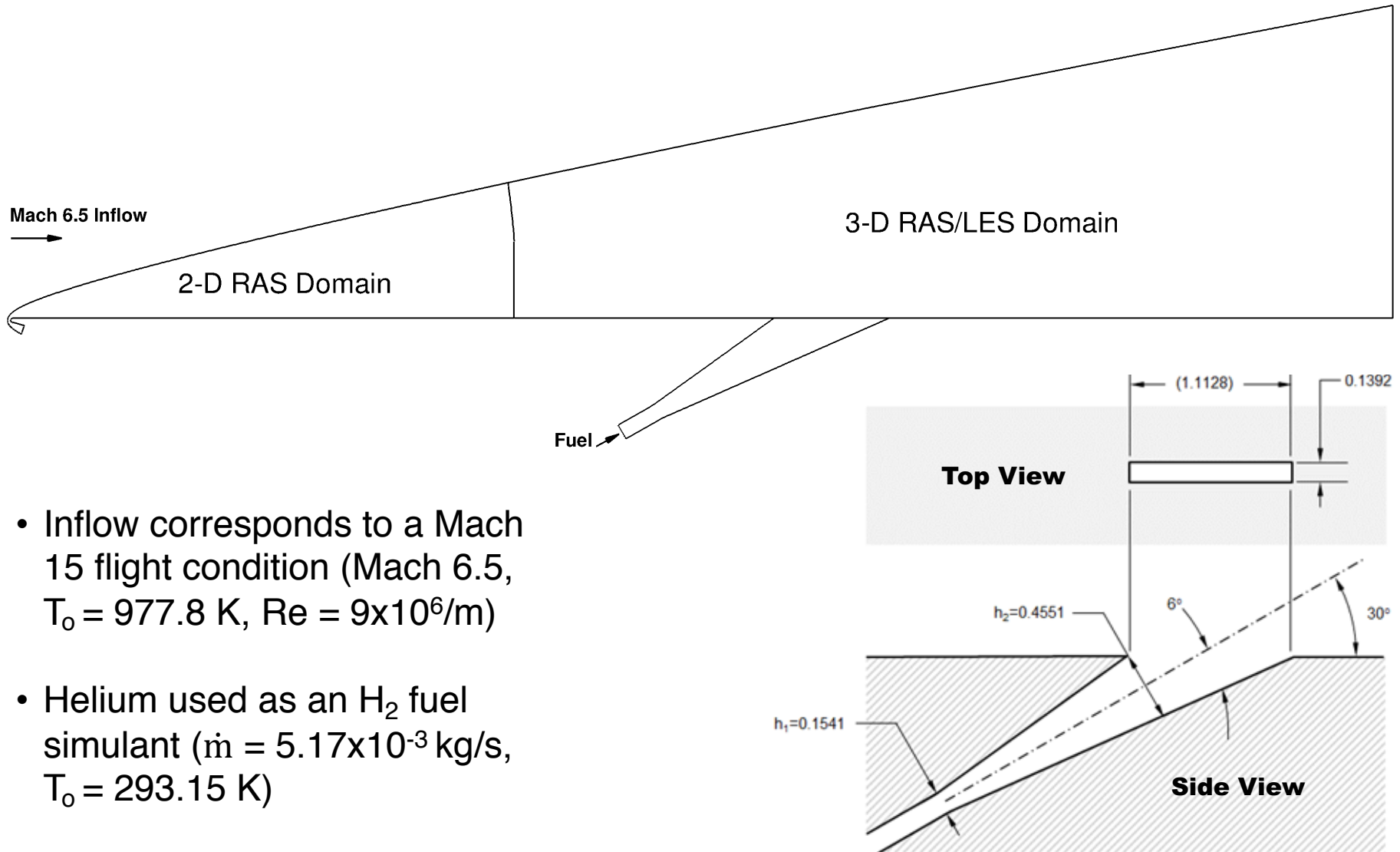
Sensitivity to RAS Turbulence/Mixing Model



ϕ Comparison of RAS with Hybrid RAS/LES

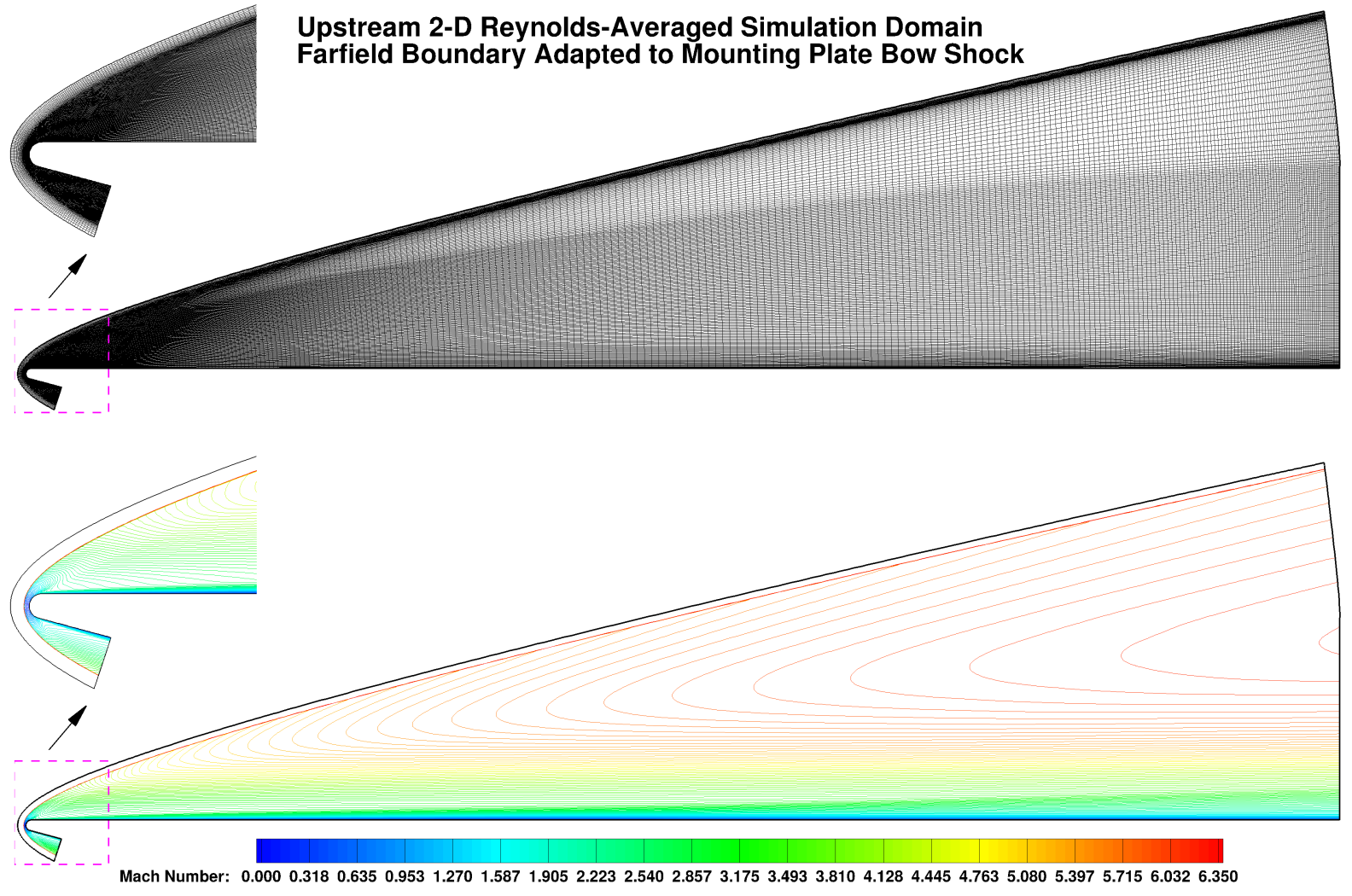


EIMP Flush-wall Injector Geometry

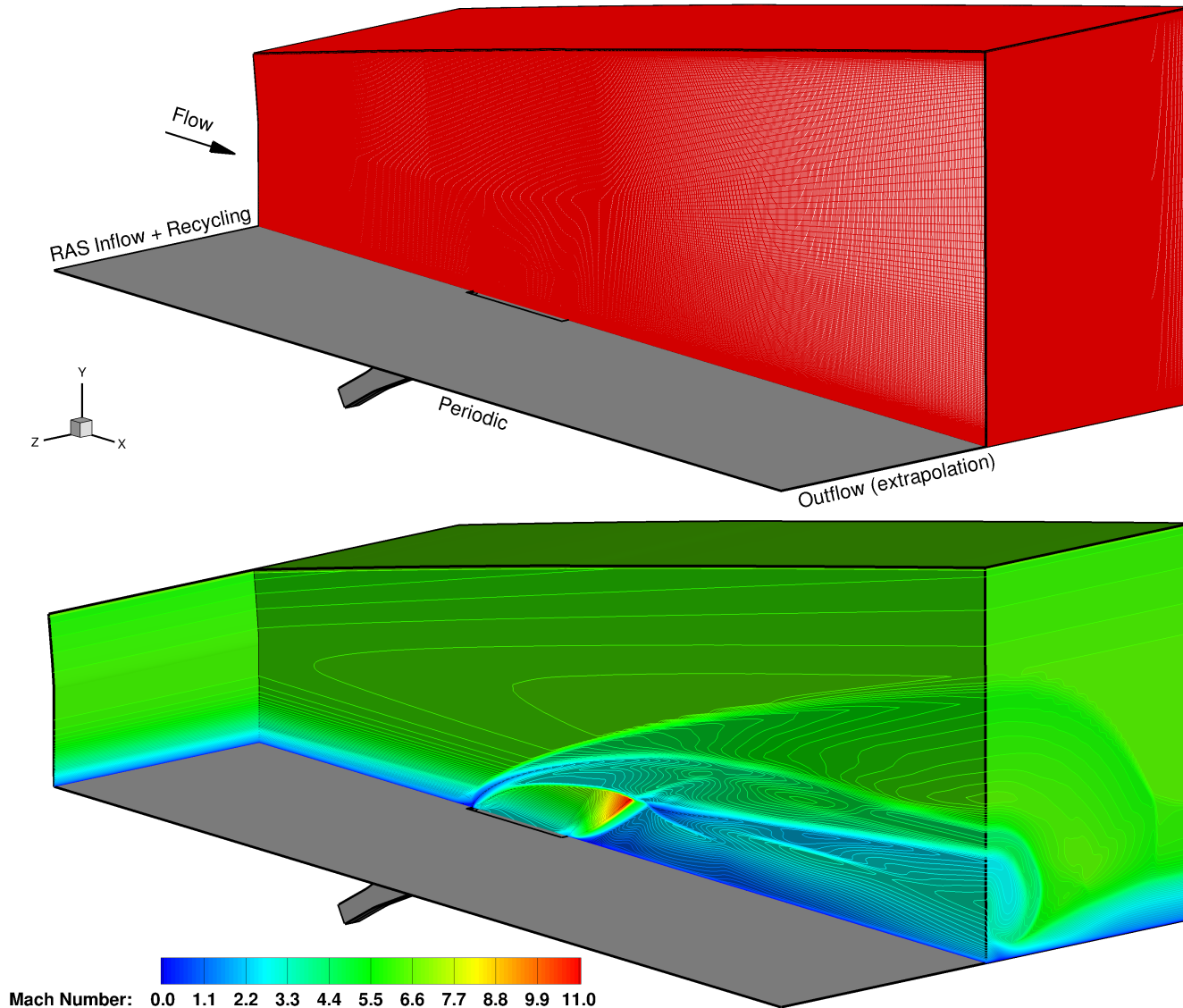


- Inflow corresponds to a Mach 15 flight condition (Mach 6.5, $T_o = 977.8$ K, $Re = 9 \times 10^6/m$)
- Helium used as an H_2 fuel simulant ($\dot{m} = 5.17 \times 10^{-3}$ kg/s, $T_o = 293.15$ K)

Flush-wall Injector Grid (upstream section)



Flush-wall Injector Grid (downstream section)



Hybrid RAS/LES Numerical Framework



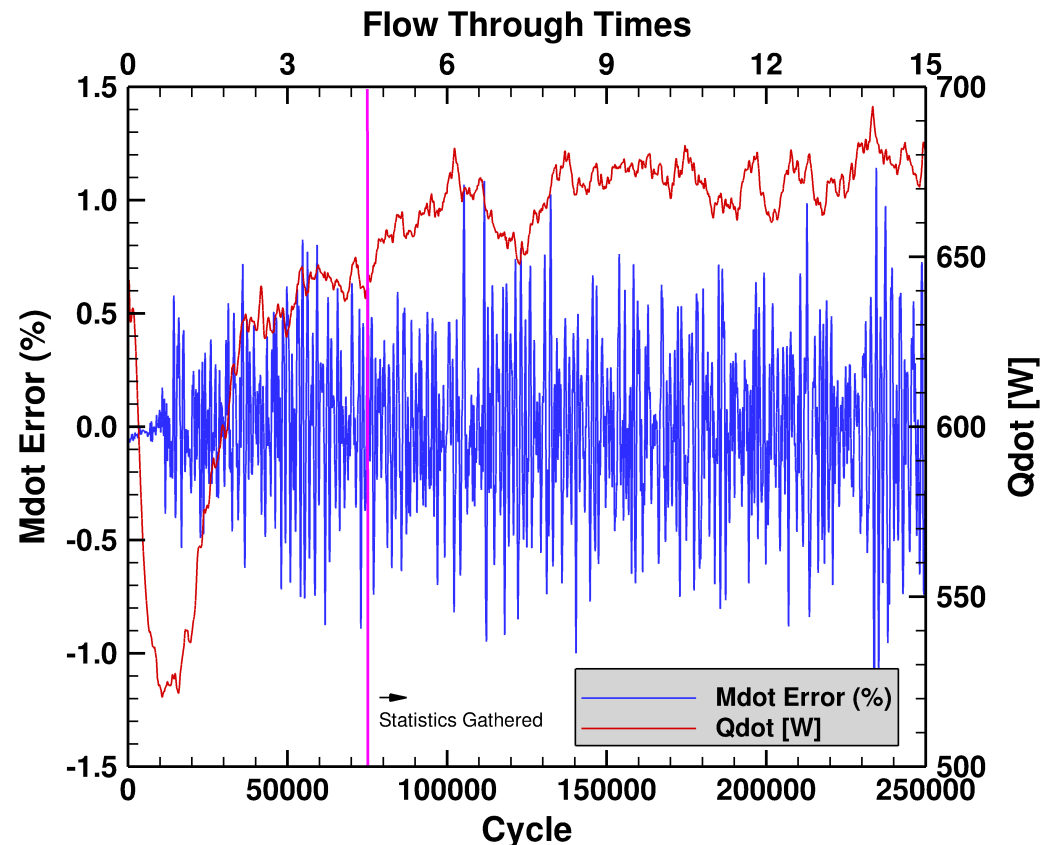
- Hybrid RAS/LES formulation blends the RAS and SGS viscosity values
 - (F) [RAS eddy viscosity] + $(1-F)$ [SGS viscosity]
- Dissipative and non-dissipative schemes are blended such that the standard dissipative formula is applied in inviscid regions and a non-dissipative formula is applied in viscous regions
 - Dissipative flux scheme: MUSCL ($\kappa=1/3$) reconstruction with 2nd order ENO limiter
 - Non-dissipative flux scheme: Symmetric 4th order reconstruction (i.e., a centered stencil)
- The hybrid flux at the cell faces is based on a weighted average of each reconstruction:
 - $q_h^{L,R} = (\psi) q^{L,R} + (1-\psi) q_{SR}$
- The Ducros (JCP-1999) switch, ψ , is used to detect inviscid (divergence dominated) regions and viscous (vorticity-dominated) regions

Hybrid RAS/LES Time Integration Process

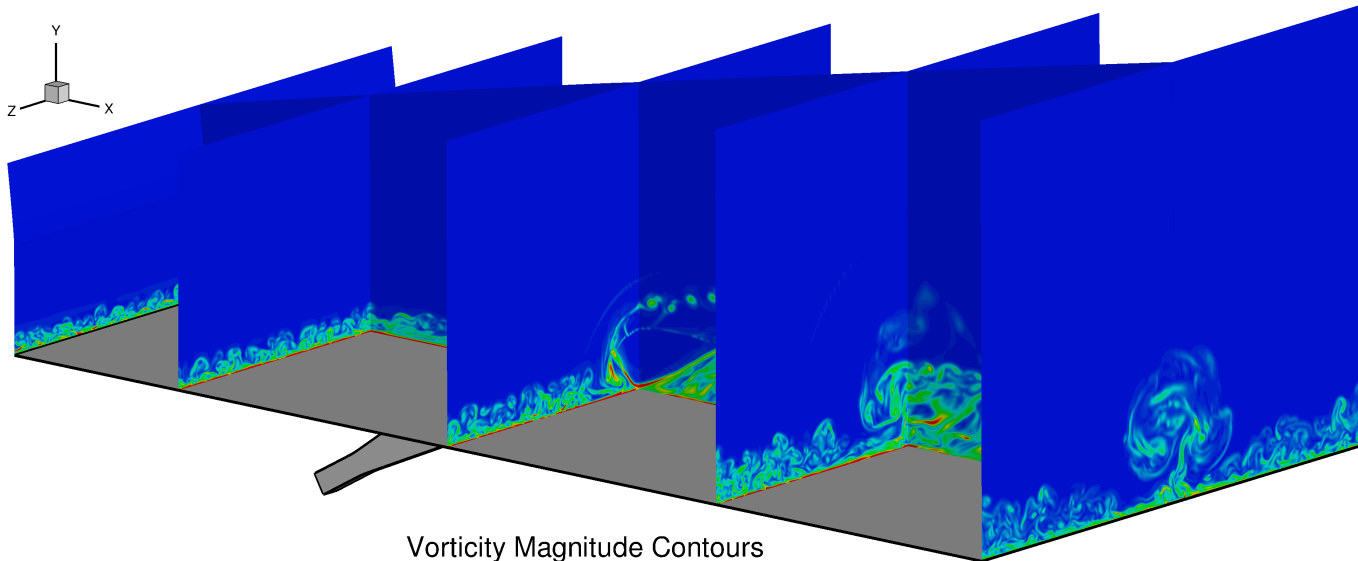
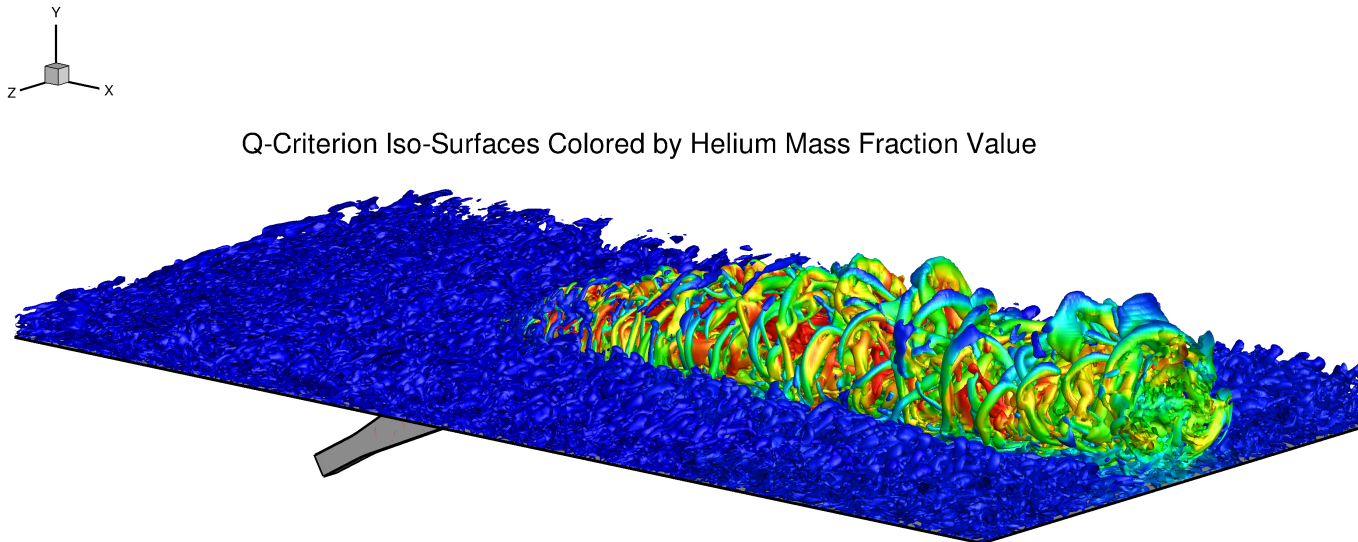


- Simulation advanced in time using a 2nd implicit backward Euler scheme
 - Subiterations were performed until the residual dropped 2 orders of magnitude
- A converged steady-state RAS solution was taken as the initial condition

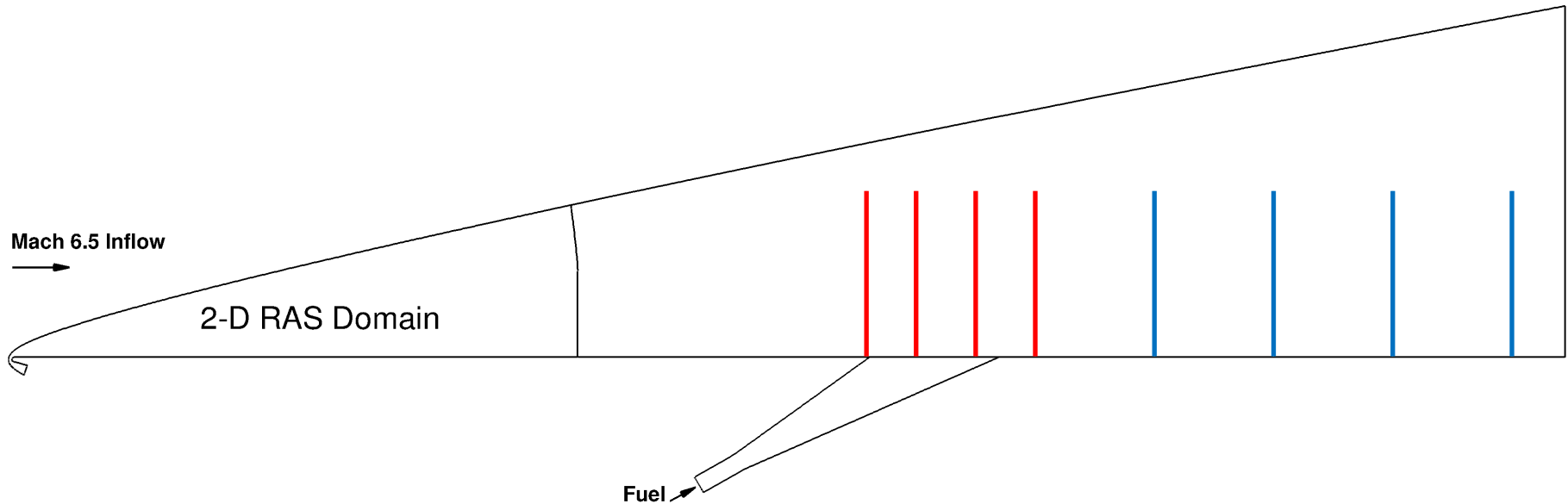
- Time step = $0.01 \mu\text{s}$
- Cell residence time = $0.1 \mu\text{s}$
- Flow through time = 0.165 ms
- 16,500 time steps required to advance 1 flow through time



Visualization of Turbulence Structures



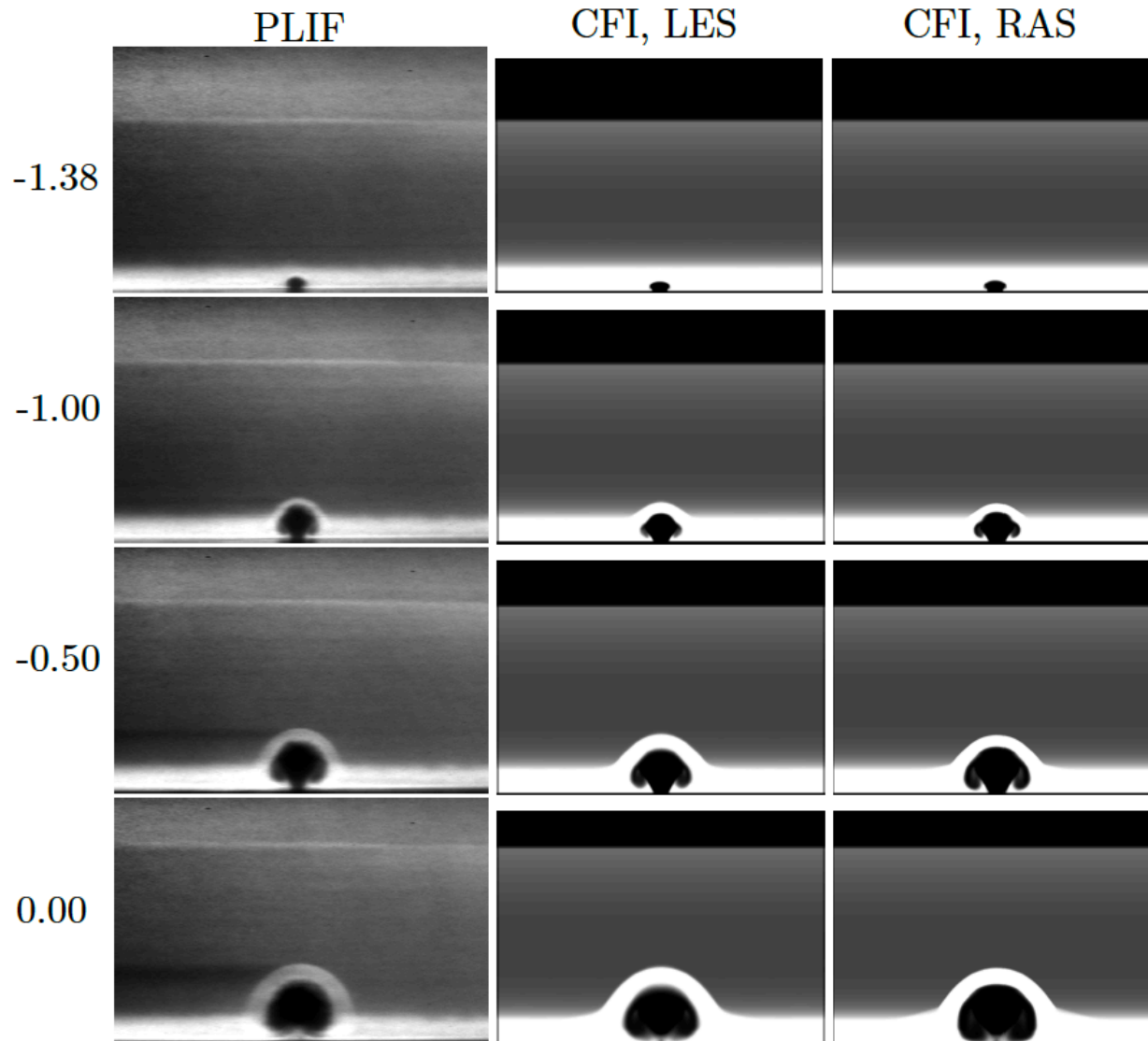
Plume Characterization via NO PLIF Imaging



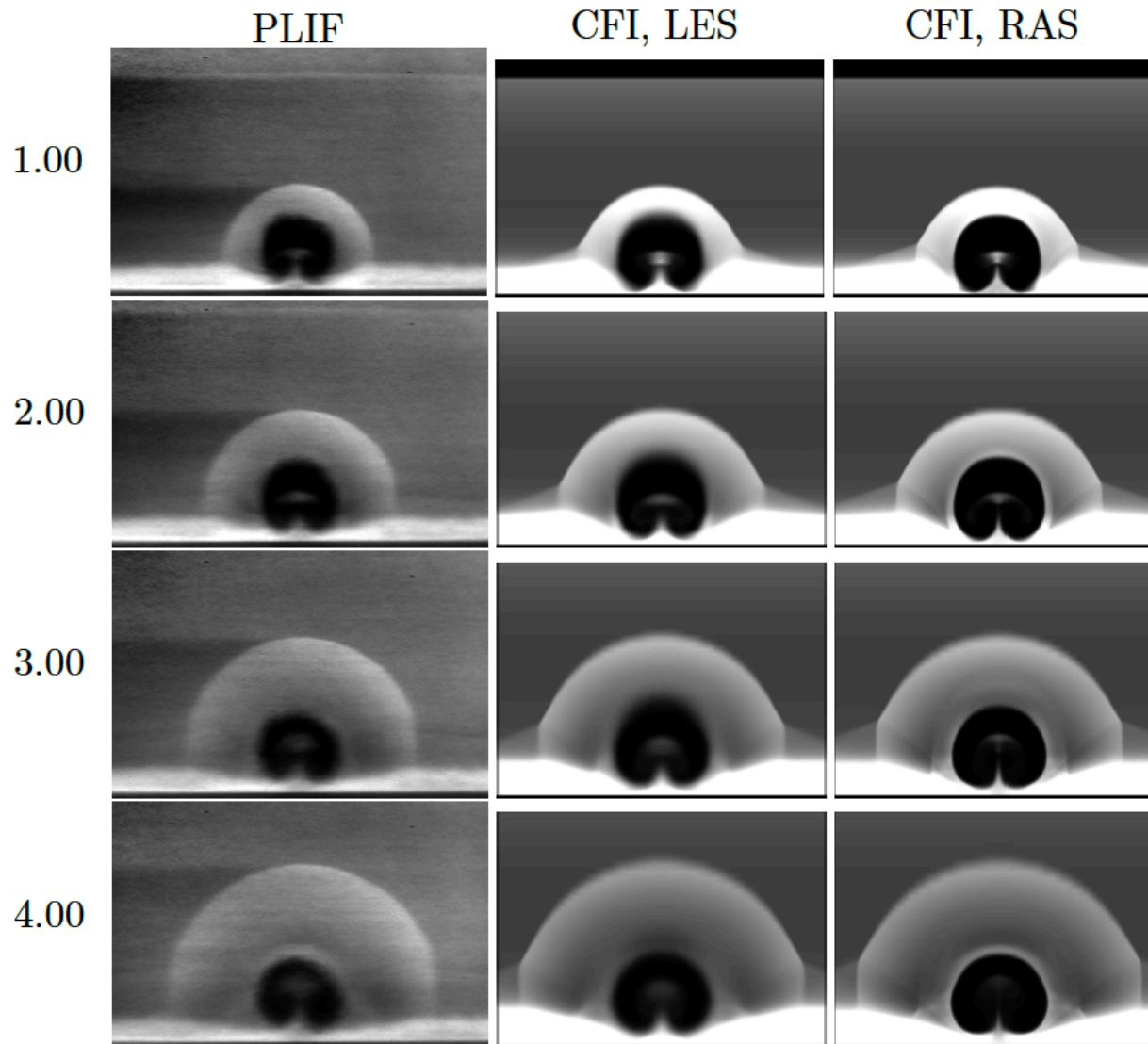
- Nitric Oxide Planar Laser-Induced Fluorescence (NO PLIF) chosen to visualize the injected fuel plume structure
 - NO is naturally present in the NASA Langley Arc-Heated Scramjet Test Facility
- CFD data processed using a theoretical fluorescence model to compare with the NO PLIF visualizations (Computational Flow Imaging)
 - Fluorescence model sensitive to NO composition, pressure, temperature and velocity

Plume Visualization via NO PLIF

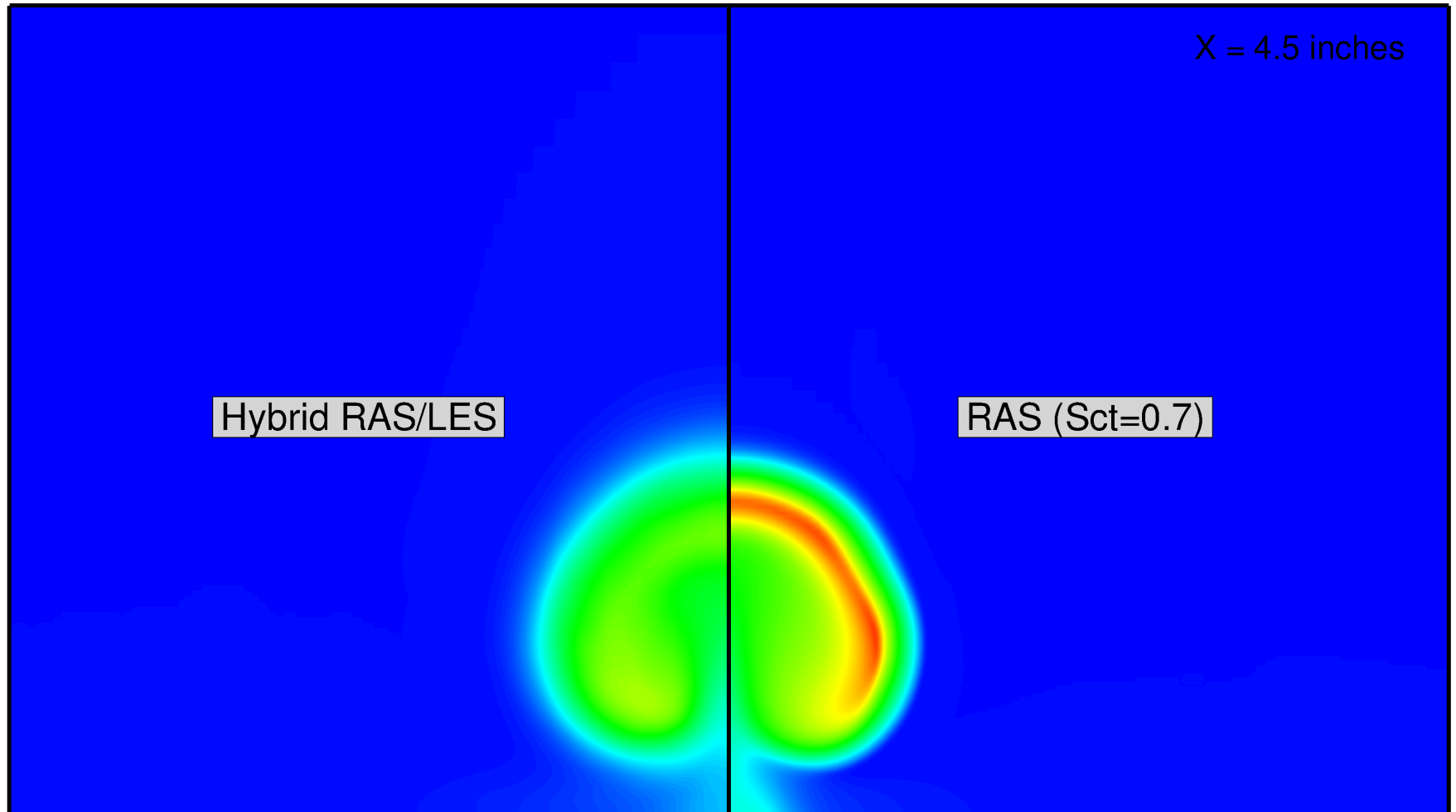
(Drozda et al., AIAA 2018-5379)



Plume Visualization via NO PLIF (continued)



RAS and Hybrid RAS/LES Helium Plumes



He Mass Fraction: 0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

Summary



- **Scramjet propulsive flowpaths are extremely challenging to model accurately**
- **Epistemic uncertainty associated with RAS modeling choices are often dominant sources of uncertainty**
 - SRS can reduce this uncertainty, but the cost is prohibitive → RAS will continue to be the primary CFD tool
 - EIMP wall clock times: RAS cost = 9 hours, RAS/LES = 560 hours
- **Limited studies to date suggest that SRS can be effectively leveraged to calibrate key RAS modeling choices**
- **An effort is underway to use this strategy for simulations supporting the NASA Enhanced Injection and Mixing Project**
- **Initial RAS and SRS results for a flush wall concept were shown and comparisons made to NO PLIF images**

Summary

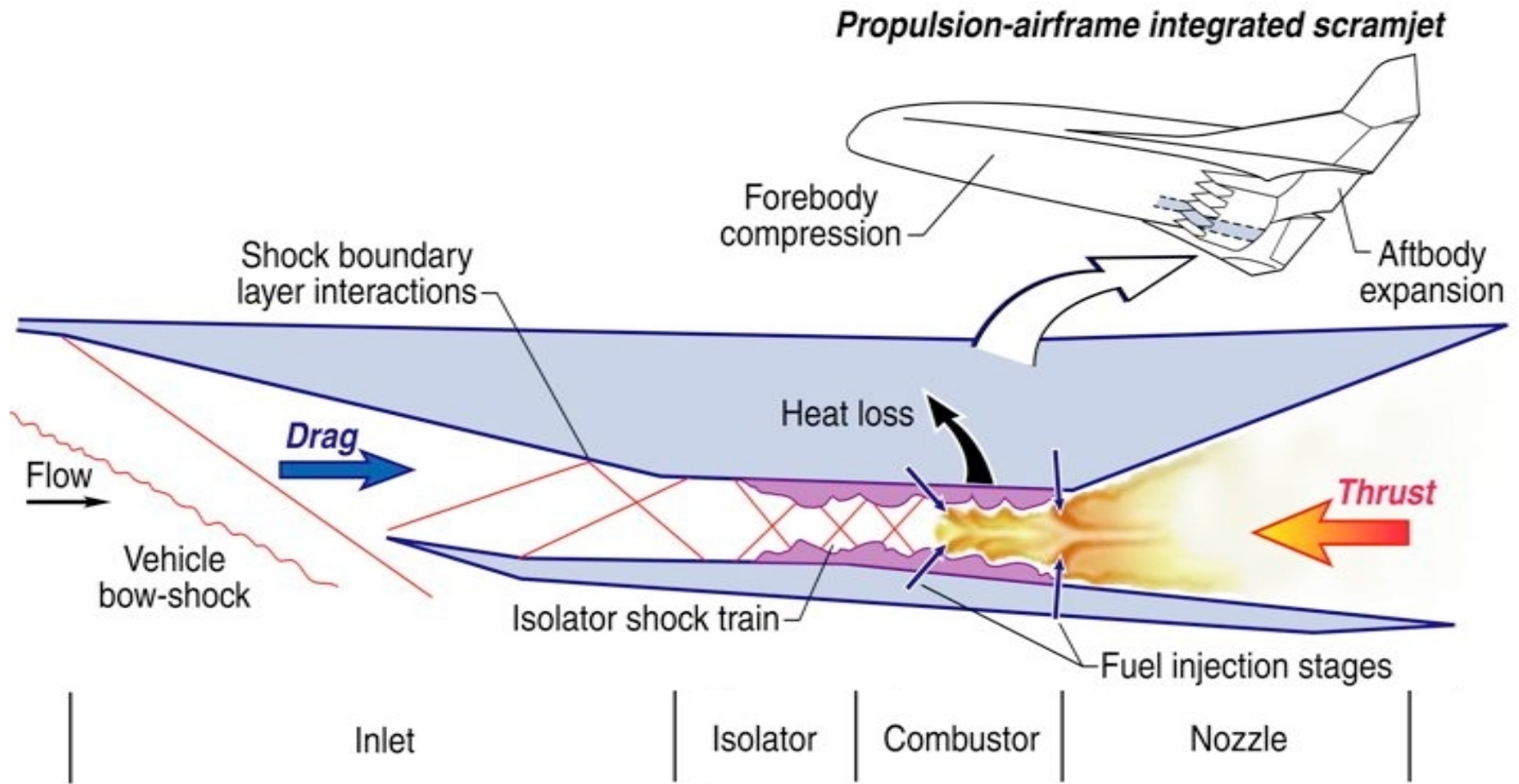


- **Some discrepancies with NO PLIF measurements were noted, which include:**
 - Slight boundary layer thickness mismatch
 - Over penetration of the computed fuel plume
 - Exaggerated plume shock/boundary layer interaction
- **Refined grids are needed to assess grid sensitivities with the SRS**
- **Once verified, the SRS will be used to calibrate the Sc_t value and turbulence model choices for subsequent injector optimization exercises**

Back-up Slides ...



Scramjet Engine Flow Features ...



Hybrid RAS/LES Formulation



- Present formulation can be regarded as a wall-modeled LES
 - SBLI require resolved turbulent content in the attached boundary layer
 - Flush wall injection likely will require resolved content as well
- Hybrid RAS/LES modeled viscosity
 - (F) [RAS eddy viscosity] + $(1-F)$ [SGS viscosity]
- Blending function (F) designed to transition near the outer edge of the log layer (AIAA 2010-0111) :

$$F = \frac{1}{2} \left\{ 1 - \tanh \left[5 \left(\frac{\kappa}{\sqrt{C_\mu}} \eta^2 - 1 \right) - \phi \right] \right\}$$
$$\ell = \sqrt{\frac{\nu}{C_\mu \omega}}$$
$$\eta = \frac{d}{\alpha \ell}$$

- Plan to implement a more recent blending strategy that is not BL specific and free of user-specified input (AIAA Journal, Vol. 49, 2011)

Inflow Specification – Recycling/Rescaling



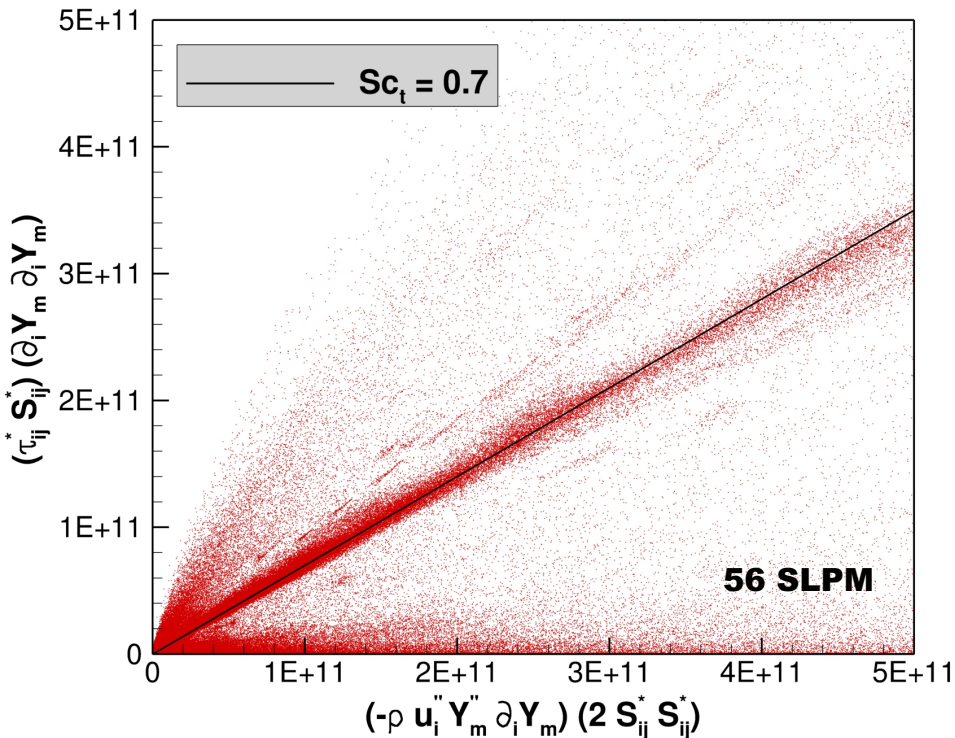
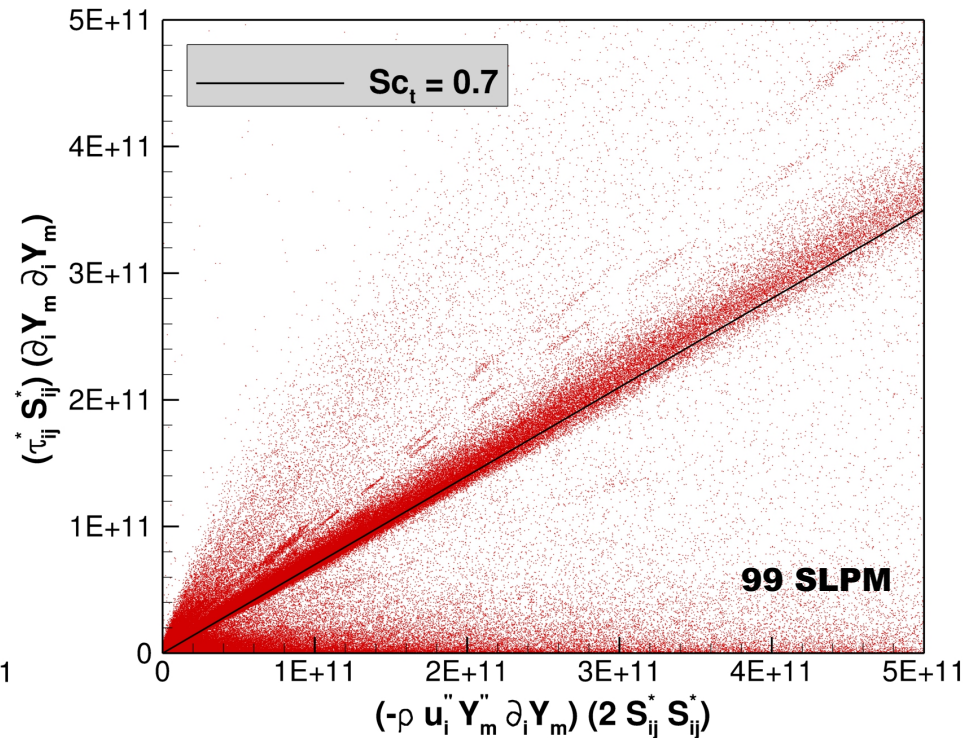
- Recycling/Rescaling to allow development and sustainment of resolved turbulent structures (AIAA 2010-1099)
 - The idea is to extract the solution at some downstream station, properly rescale the data, and recycle the turbulent content back to the inflow plane.
 - Only the fluctuations are recycled to avoid any drift in the inflow mean flow properties.
 - Velocity fluctuations are recycled and scaled based on known boundary layer scaling properties.
 - Temperature fluctuations are obtained from the velocity fluctuations using Morkovin's hypothesis that total temperature fluctuations are negligible.
 - Pressure fluctuations are recycled without any rescaling.
 - An intermittency function is applied near the edge of the inflow boundary layer to prevent recycled fluctuations from corrupting the freestream.
 - A random spanwise shift procedure is used to mitigate the formation of large-scale structures (rollers) during the recycling process.

Turbulent Transport Correlation Calibration



$$\tau_{ij} = 2\mu_t \left(S_{ij} - \frac{1}{3} \delta_{ij} \frac{\partial \tilde{u}_k}{\partial x_k} \right) - \frac{2}{3} \delta_{ij} \bar{\rho} \tilde{k}, \quad \bar{\rho} \widetilde{u_i'' Y_m''} = -\frac{\mu_t}{Sc_t} \frac{\partial \tilde{Y}_m}{\partial x_i}$$

$$\mu_t = \frac{\left(\tau_{ij} + \frac{2}{3} \delta_{ij} \bar{\rho} \tilde{k} \right) \left(S_{ij} - \frac{1}{3} \delta_{ij} \frac{\partial \tilde{u}_k}{\partial x_k} \right)}{2 \left(S_{ij} - \frac{1}{3} \delta_{ij} \frac{\partial \tilde{u}_k}{\partial x_k} \right) \left(S_{ij} - \frac{1}{3} \delta_{ij} \frac{\partial \tilde{u}_k}{\partial x_k} \right)} \equiv \frac{\tau_{ij}^* S_{ij}^*}{2 S_{ij}^* S_{ij}^*}, \quad \frac{\mu_t}{Sc_t} = \frac{-\bar{\rho} \widetilde{u_i'' Y_m''} \frac{\partial \tilde{Y}_m}{\partial x_i}}{\frac{\partial \tilde{Y}_m}{\partial x_i} \frac{\partial \tilde{Y}_m}{\partial x_i}}$$



Comparison of Mixing Efficiency

