

An Introduction to Hybrid RAS/LES Methods: Techniques, Grid Requirements, Limitations

Robert A. Baurle
NASA Langley Research Center





- **Motivation**
- **Hybrid RAS/LES**
 - Methods
 - Grid Requirements
 - Numerics
- **Application**
 - Hybrid RAS/LES used for RAS calibration
- **Summary**

Motivation: Reduce Model Form Uncertainty



- **Current SoA for CFD analysis used for engineering purposes are Reynolds-averaged simulations:**
 - All scales of turbulence are modeled → often leading source of uncertainty.
 - Boussinesq approximation → linear eddy viscosity models (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 but with a substantial increase in computational cost).
 - Smaller scales more universal in nature (presumably easier to model)
 - Model uncertainty (related to turbulence) can be reduced with grid resolution.
 - SRS is less effective at reducing model uncertainty for TCI.



- **Wall-modeled scale resolving simulation approaches**
 - LES + Wall Stress Model
 - LES is performed everywhere, but an auxiliary set of equations (wall-stress model) is solved within the inner “layer”.
 - Wall-stress model takes the instantaneous LES velocity at some distance off the wall, and provides the instantaneous wall stress back to the LES solver as a boundary condition.
 - Hybrid RAS/LES
 - A single grid that covers the full domain is used that satisfies standard LES resolution requirements in the outer part of the boundary layer, but resorts to RAS resolution requirements in the inner part (i.e., the grid resolves the viscous length scale in the wall-normal direction but not in the wall-parallel directions).
- **Most early hybrid RAS/LES methods were never intended to support resolved fluctuations in the BL (i.e., DES and DDES)**
 - These approaches permit RAS grid requirements in regions with attached boundary layers → not the focus here.

Hybrid RAS/LES Framework

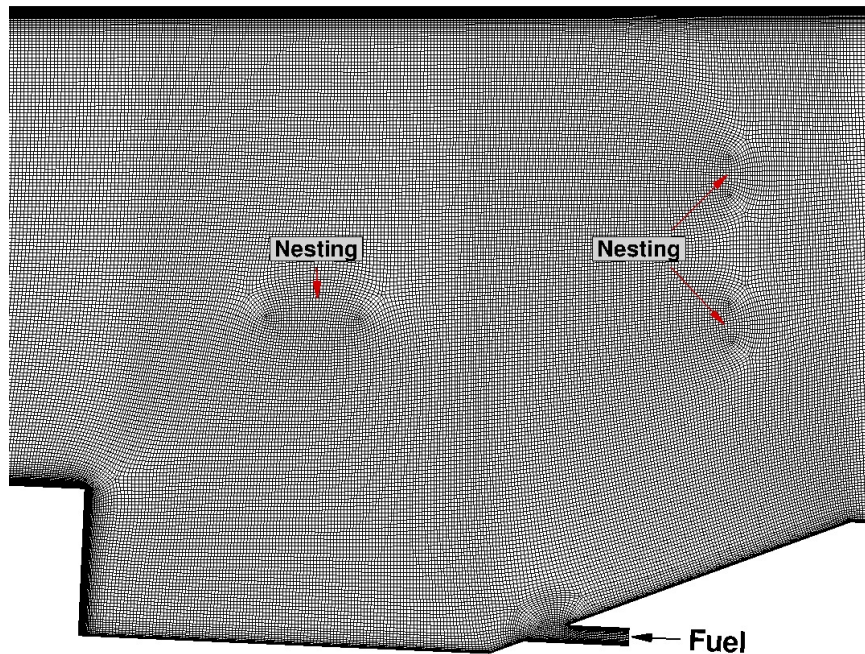
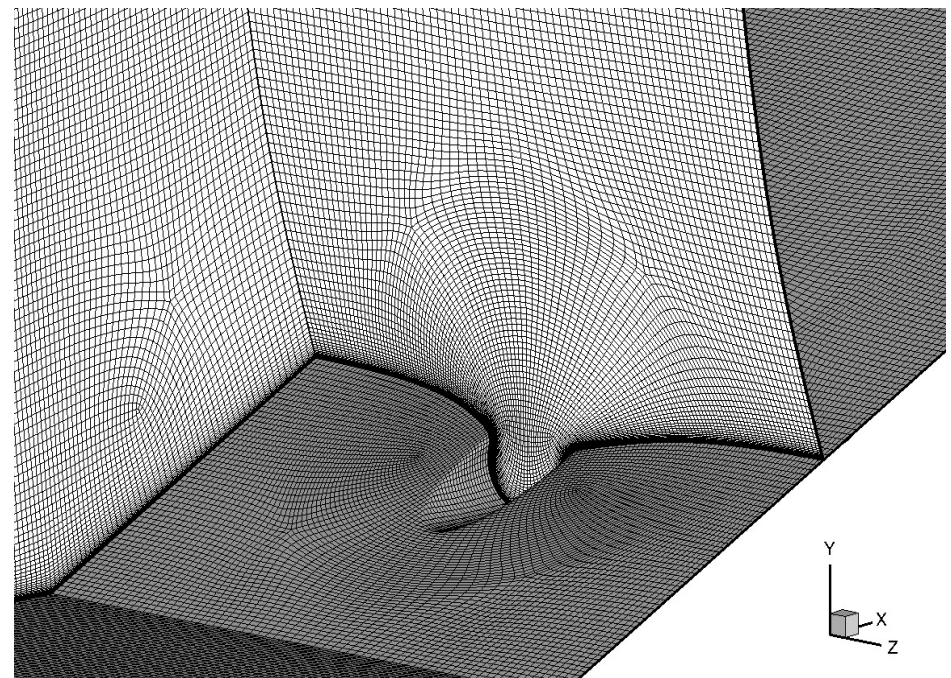


- **Hybrid RAS/LES attempt to resolve a significant fraction of turbulence in free shear regions and the outer portion of turbulent boundary layers.**
 - Sub-grid models that depend on cell length used to model the small scales.
- **No attempt is made to resolve turbulent scales in the inner portion of turbulent boundary layers**
 - The range of turbulent scales in the inner layer is small, essentially requiring DNS resolution very close to the wall.
 - Rely more on models instead, i.e., RAS level of modeling needed for inner layer.
- **This strategy implies some sort of blending of LES with RAS concepts:**
 - Blend SGS viscosity with RAS viscosity: F [eddy viscosity] + $(1-F)$ [SGS viscosity]
 - Blend SGS and RAS length scales: F [RAS length scale] + $(1-F)$ [SGS length scale]
- **For hybrid RAS/LES to be effective:**
 - Grid in regions where $F \ll 1$ must provide enough grid resolution to capture a high fraction of the turbulence energy (80 — 90% of scales).
 - Numerics in regions where $F \ll 1$ should have low dissipative qualities to maximize the range of scales resolved by the grid.

Hybrid RAS/LES Grid Spacing Requirements



- **Assuming low dissipation numerics are used ...**
 - Nearly isotropic elements should be used in actively turbulent regions when $F \ll 1$.
 - Spacing should be in the neighborhood of $1/20^{\text{th}}$ of the viscous layer thickness.
 - Anisotropic elements limited to the inner layer to allow grid clustering to the wall.



- **Time step must also be small enough to resolve/track the time evolution of the eddy structures.**
 - Implies time step must be on the order of the fluid residence time within each cell.

Hybrid RAS/LES Low-Dissipation Numerics

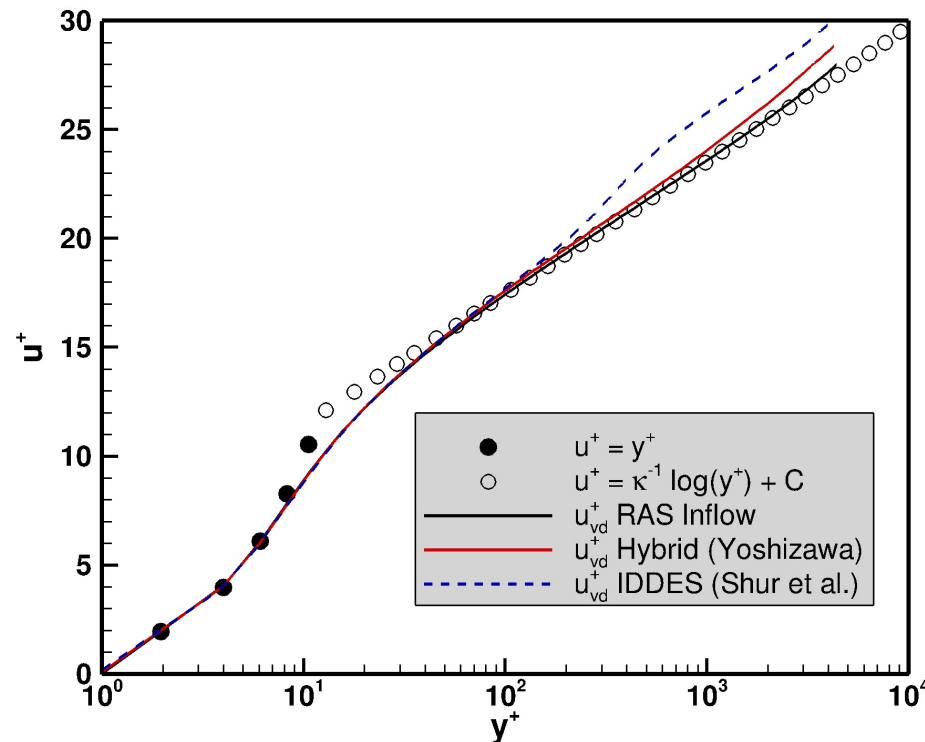


- Dissipative and nondissipative schemes are combined via a hybridization strategy:
 - Hybrid flux via Symmetric Reconstruction: $q_h^{L,R} = (\psi) q^{L,R} + (1-\psi) q_{SR}$
 - Hybrid flux via SBP α -split scheme: $F_h^{L,R} = (\psi) F_{diss} + (1-\psi) F_{\alpha-split}$
- Dissipative variable reconstruction for inviscid flux evaluation ($q^{L,R}$):
 - 2nd-order MUSCL-based variable reconstruction → avoid TVD limiters!
 - PPM scheme of Collela and Woodward (JCP-1984)
 - WENO (pick your flavor)
- Nondissipative inviscid flux construction:
 - Symmetric Reconstruction (centered stencil)
 - 2nd-, 4th-, or 6th-order order reconstruction operators (q_{SR})
 - Summation-by-Parts α -split flux (2nd-, 4th-, or 6th-order)
 - Skew-symmetric scheme of Honein and Moin, J. Comp. Phys., 2004
- Hybrid switch (ψ) used to distinguish between shock-dominated regions and vorticity-dominated regions:
 - Ducros et al. (JCP-1999) or Larsson (private communication)

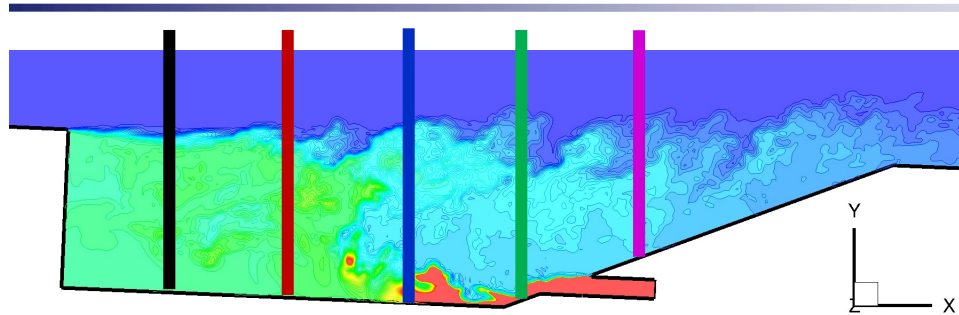
Hybrid RAS/LES Deficiencies



- Hybrid RAS/LES simulation results are notoriously sensitive to the mesh and the numerics employed.
- Injection of “realistic” turbulent structures often required to kick-start the generation of turbulent eddies.
- Log layer mismatch is a persistent problem

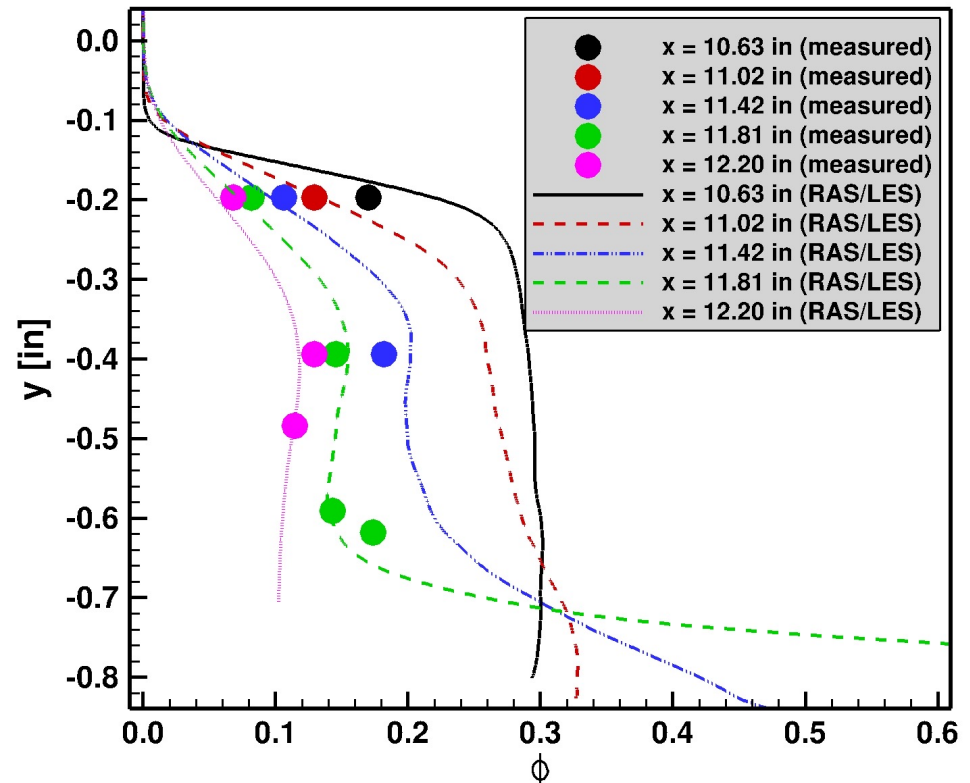


Use of SRS to Calibrate RAS Closures

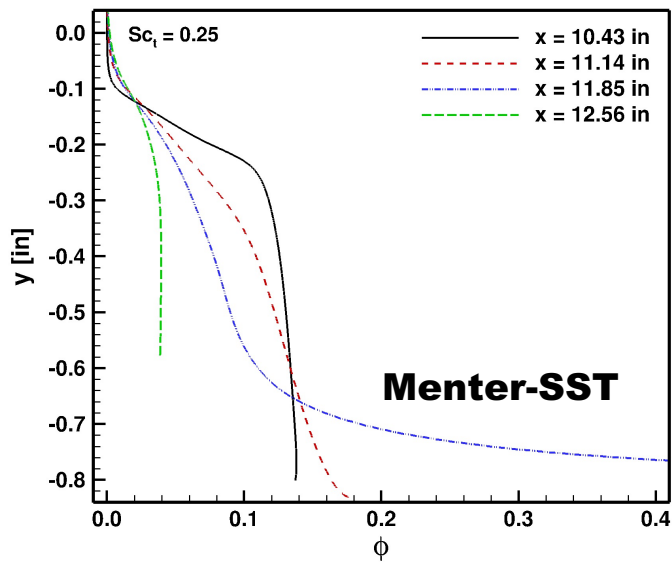
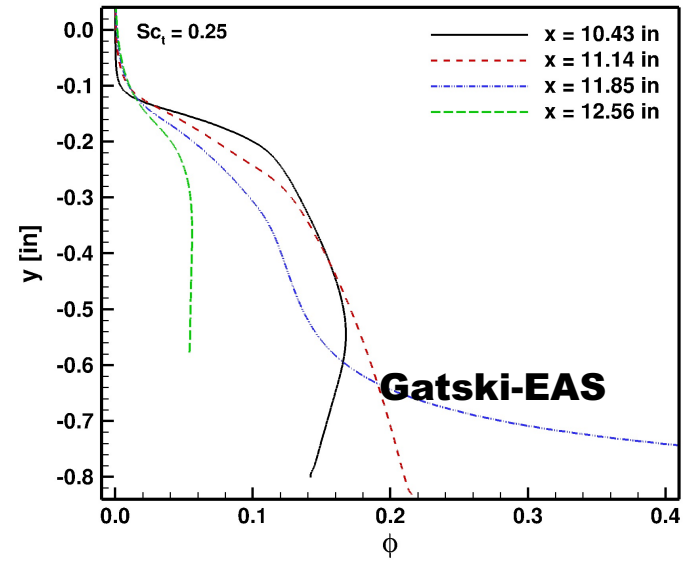
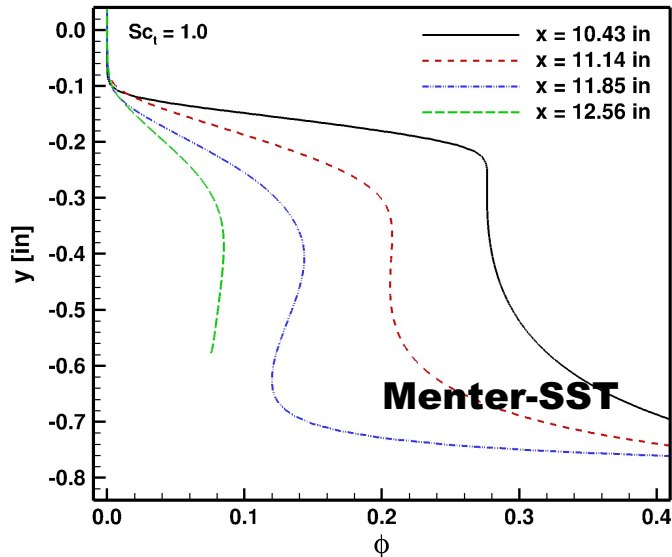
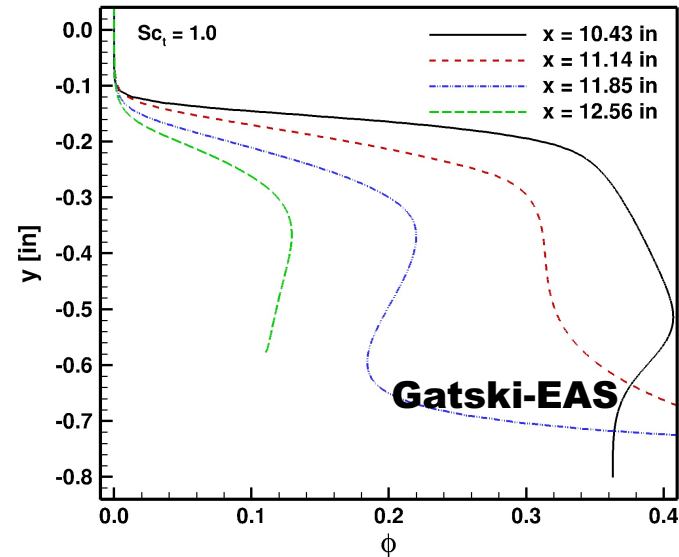


ϕ : 0.00 0.25 0.50 0.75 1.00 1.25

- Hybrid RAS/LES for Mach 2 flow past a fueled recessed cavity
- Ethylene fuel conditions:
 $\dot{m} = 56$ SLPM, $T_o = 310$ K
- Fuel/Air Equivalence Ratio measured via LIBS



Use of SRS to Calibrate RAS Closures

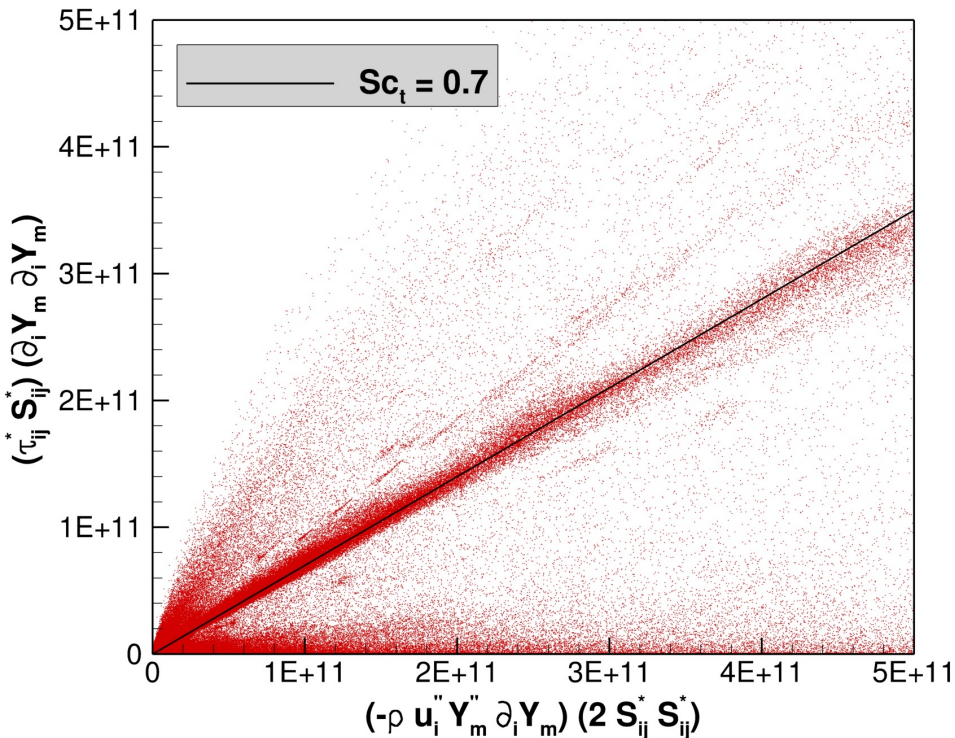
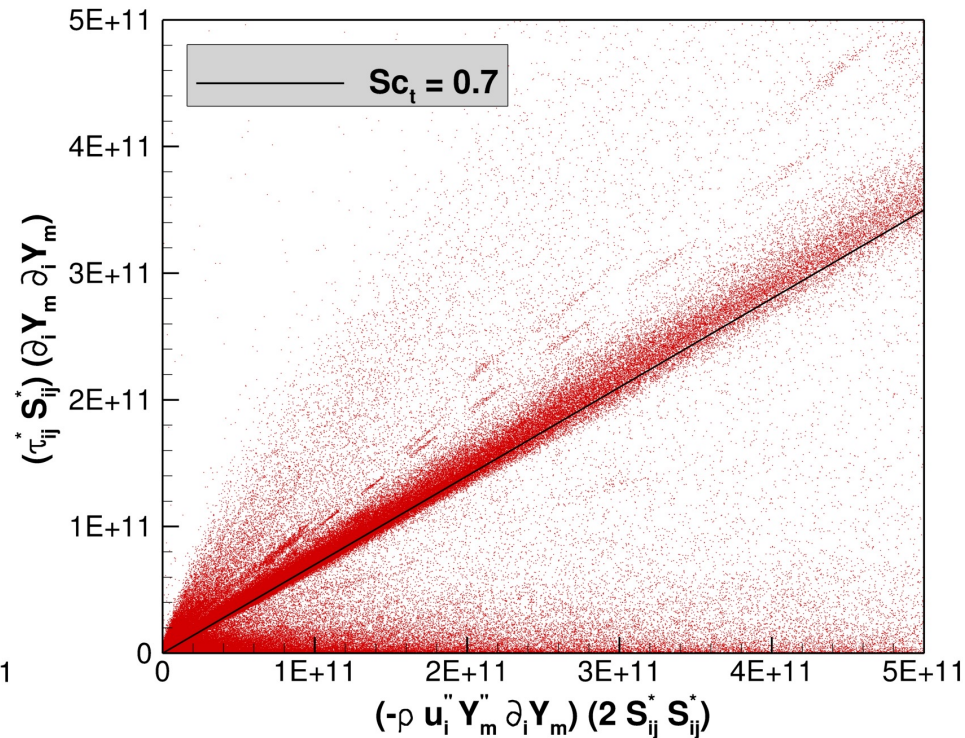


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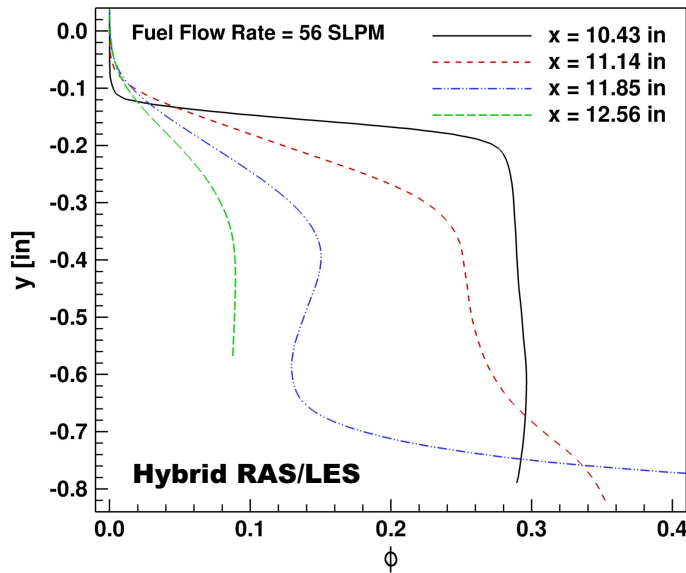
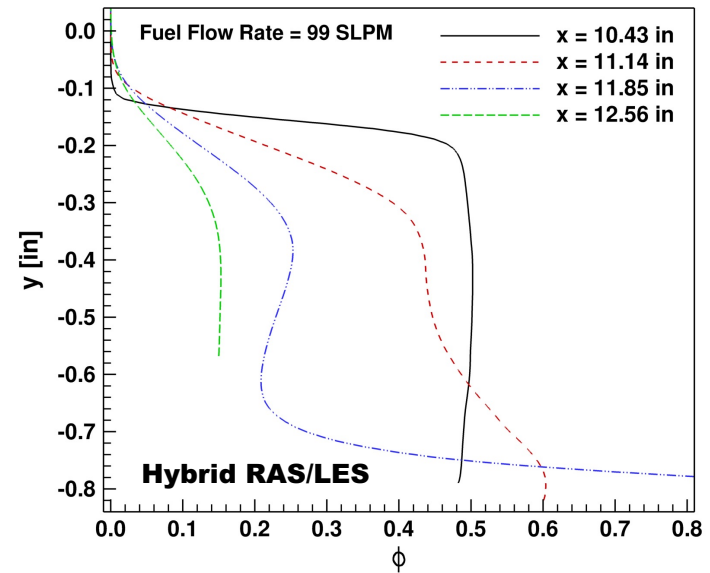
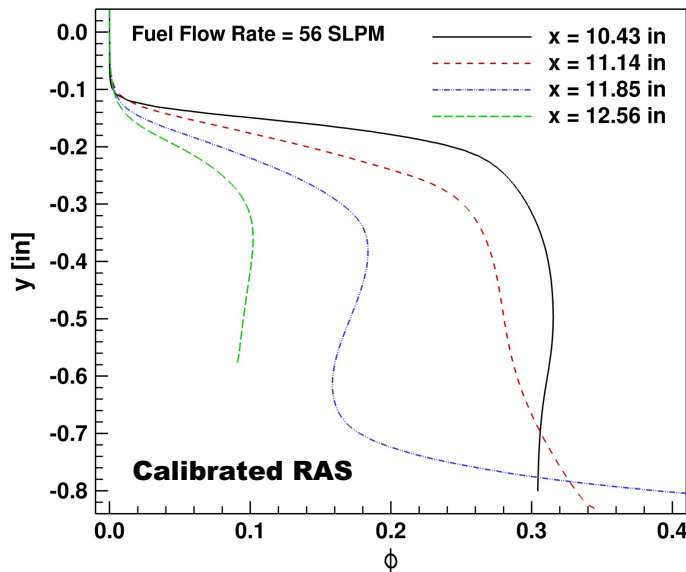
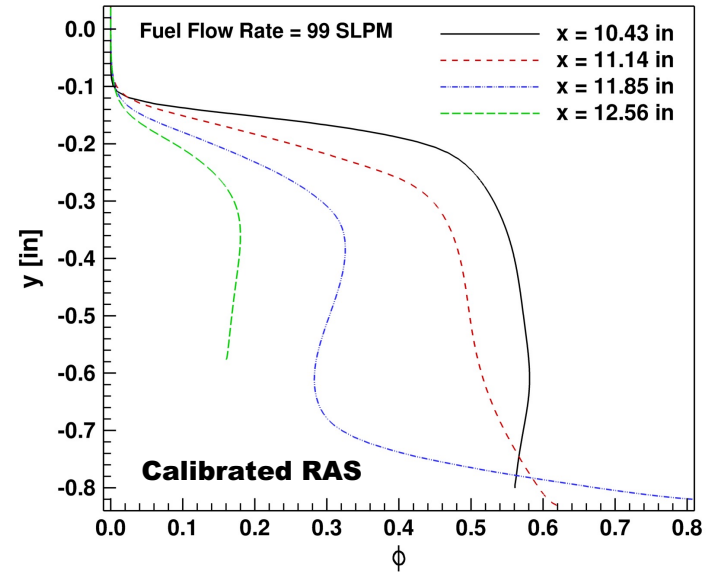


$$\tau_{ij} = 2\mu_t \left(S_{ij} - \frac{1}{3} \delta_{ij} \frac{\partial \tilde{u}_k}{\partial x_k} \right) - \frac{2}{3} \delta_{ij} \bar{\rho} \tilde{k}, \quad \bar{\rho} \widetilde{u_i'' Y_m''} = -\frac{\mu_t}{Sc_t} \frac{\partial \tilde{Y}_m}{\partial x_i}$$

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



Use of SRS to Calibrate RAS Closures



- **Hybrid RAS/LES used in WMLES methods described**
 - Blending of RAS and LES via turbulent length scales
 - Shur et al. [2008], Gritskevich [2012]
 - Blending of RAS and LES via turbulent viscosities
 - Edwards et al. [2009, 2011]
- **Hybrid RAS/LES can be expected to provide more reliable predictions of turbulent flows (as compared to RAS):**
 - free shear flows
 - wall-bounded flows with separation
 - boundary layer recovery after separation
- **Hybrid RAS/LES particularly useful for the following scenarios:**
 - improve fundamental physics understanding (universities routinely do this)
 - investigate impact of unsteady effects
 - RAS scenarios with unacceptably high uncertainty (e.g., operability bounds)
 - calibration of RAS closure models

Back-up Slides ...



