Collaborative Testing Challenge

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2022 Symposium on "Turbulence Modeling: Roadblocks, and the Potential for Machine Learning", Suffolk, VA, 27 July, 2022

1) Basic idea

- In a 2006 Physics of Fluids paper "A new methodology for Reynolds-averaged modeling based on the amalgamation of heuristic-modeling and turbulence-theory methods" Yoshizawa et al suggested using a synthesized time scale τ in several modeled terms (e.g. the "slow-term")

$$\Phi^{h}_{ij,slow} = -\frac{C_{g1}}{\tau}\left(\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij}\right) \qquad \frac{1}{\tau^2} = \frac{1}{\tau_E^2} + C_S\frac{1}{\tau_S^2} + C_\Omega\frac{1}{\tau_\Omega^2} + C_{AK}\frac{1}{\tau_{AK}^2} + C_{A\varepsilon}\frac{1}{\tau_{A\varepsilon}^2}$$

$$\tau_E = K/\varepsilon, \quad \tau_S = 1/\sqrt{S_{ij}^2}, \quad \tau_\Omega = 1/\sqrt{\Omega_{ij}^2}, \quad \tau_{AK} = 1/\sqrt{\left(\frac{1}{K}\frac{DK}{Dt}\right)^2} \quad \tau_{A\varepsilon} = 1/\sqrt{\left(\frac{1}{\varepsilon}\frac{D\varepsilon}{Dt}\right)^2}.$$

- They used this idea to derive an eddy viscosity $k - \varepsilon$ model and a "second order" EARSM

- Accounting for strain and rotation time scales, they obtained good results for some canonical flow (channel flow, rotating pipe, …)

1) Basic idea

- They did not include a time scale based on $\tau_{dk} = \frac{k}{Dk/Dt}$ although they state that this would be important for e.g. flow separation behind sharp steps

Idea: Include τ_{Ak} (and others) in the synthesized time scale expression

- *Use it in a full RSM (accounting for near wall effects) to avoid loss of accuracy through EARSM assumptions*
- *RSM without near wall distance that can be used in HRLES*
- *Use data driven approach to find constants $C_S, C_{Ak}, \ldots$*

2) Model and CFD solver

- Use the elliptic blending RSM idea of Manceau & Hanjalic
- Further improve near wall behavior by using the homogenous dissipation rate to model the dissipation rate tenors (Stoellinger et al AIAA Paper 2015-2926)

$$\frac{\partial \tau_{ij}}{\partial t} + \overline{u}_j \frac{\partial \tau_{ij}}{\partial x_j} = P_{ij} + \Phi^*_{ij} - \varepsilon^h_{ij} + \frac{\partial}{\partial x_k}\left[\left(0.5\nu\delta_{kl} + C_k \frac{k}{\varepsilon^h}\tau_{kl}\right)\frac{\partial \tau_{ij}}{\partial x_l}\right],$$

$$\varepsilon^h = \varepsilon - 0.5\nu \frac{\partial^2 k}{\partial x_l x_l} \qquad \varepsilon^h_{ij} = (1 - f_\alpha)\frac{\tau_{ij}}{k}\varepsilon^h + f_\alpha \frac{2}{3}\varepsilon^h \delta_{ij}$$

Rationale: near wall anisotropy of dissipation tensor can be better modeled

Redistribution model (elliptic blending)

$$\Phi^*_{ij} = (1 - f_\alpha)\Phi^w_{ij} + f_\alpha \Phi^h_{ij}$$

Φ^w_{ij} → near wall model

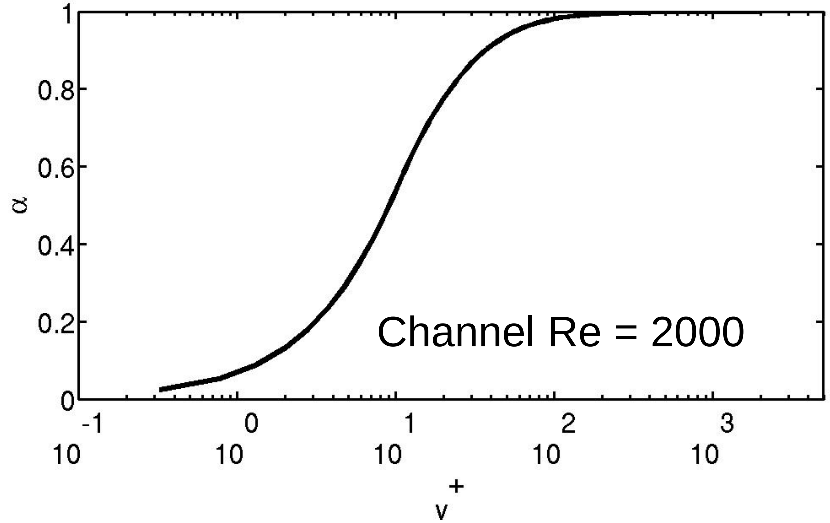
Φ^h_{ij} → homogeneous model: e.g. SSG or LRR

2) Model and CFD solver

blending function: $f_\alpha = \alpha^3$ $\qquad \alpha - L_d^2 \nabla^2 \alpha = 1$ $\qquad \alpha|_{wall} = 0$, $\alpha|_\infty = 1$

with "Durbin" limited length scale

$$L_d = max\left(C_L \frac{k^{3/2}}{\varepsilon^h}, C_\eta \frac{\nu^{3/4}}{(\varepsilon^h)^{1/4}}\right)$$



Define "wall" normal vector $\vec{n} = \frac{\nabla \alpha}{\| \nabla \alpha \|}$

Near wall model:

$$\Phi_{ij}^w = -5 \frac{\varepsilon^h}{k} \left(\tau_{ik} n_j n_k + \tau_{jk} n_i n_k - \frac{1}{2} \tau_{kl} n_k n_l \left(n_i n_j + \delta_{ij} \right) \right)$$

2) Model and CFD solver

Homogeneous Dissipation rate model:

$$\frac{\partial \varepsilon^h}{\partial t} + \overline{u}_j \frac{\partial \varepsilon^h}{\partial x_j} = C_{\varepsilon 1} P \frac{\varepsilon^h}{k} - C_{\varepsilon 2} f_\varepsilon \frac{\tilde{\varepsilon}^h \varepsilon^h}{k} + E_\varepsilon + \frac{\partial}{\partial x_k}\left[\left(0.5\nu\delta_{kl} + C_\varepsilon \frac{k}{\varepsilon^h}\tau_{kl}\right)\frac{\partial \varepsilon^h}{\partial x_l}\right]$$

$$f_\varepsilon = 1 - \frac{C_{\varepsilon 2} - C_{\varepsilon 1}}{C_{\varepsilon 2}} \exp\left[-(7\alpha)^5\right]$$

Instead of $(Re_t/6)^2$

- Model implemented in OpenFOAM v2206
- Incompressible SIMPLEC based solver
- Under-relaxation for τ_{ij} and ε^h typically < 0.5
- Used TMR suggested inflow values for RSM models where available

2) Model and CFD solver

Problematic behavior in 2D-ZPG found

- With the low free stream turbulence values, the near-wall (α values) region remains too thick
- Likely caused by use of L_d

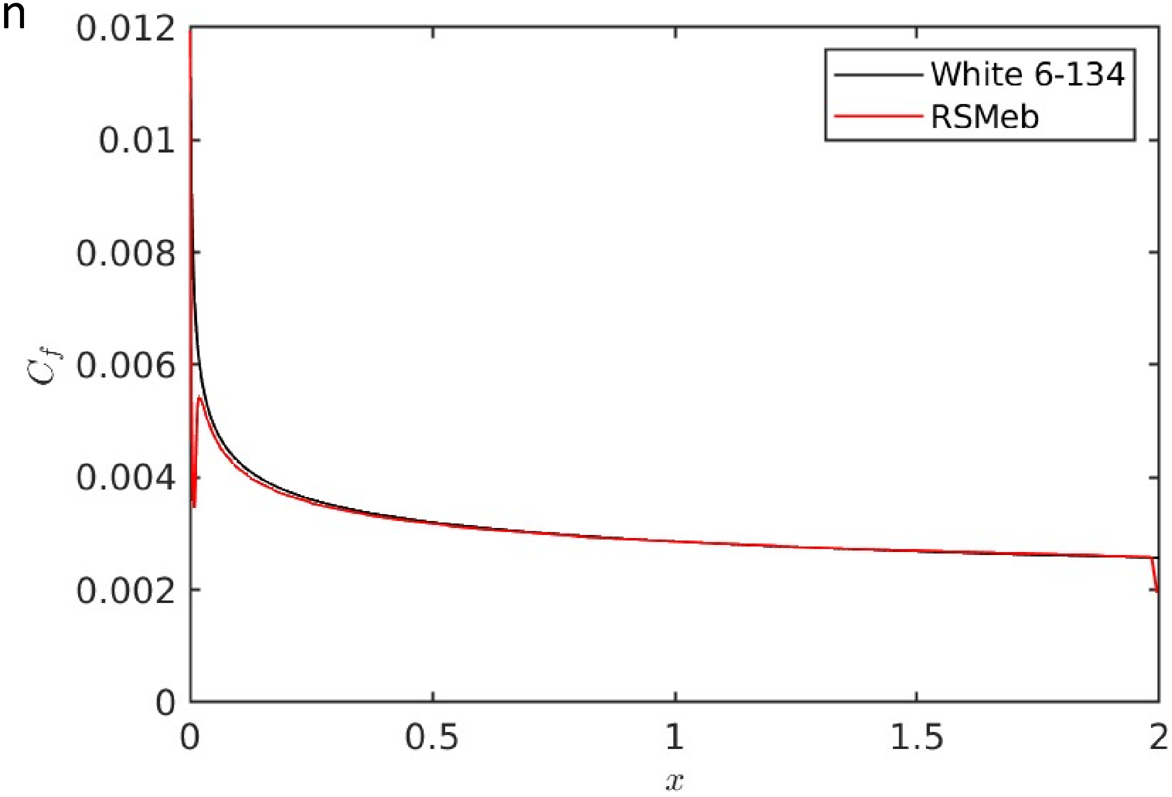
$$L_d = max\left(C_L\frac{k^{3/2}}{\varepsilon^h}, C_\eta\frac{\nu^{3/4}}{(\varepsilon^h)^{1/4}}\right)$$

- Needed to turn off the limiter for $y^+ > 20$
- Brings back a geometrical near wall distance

3) 2D-ZPG results

Details

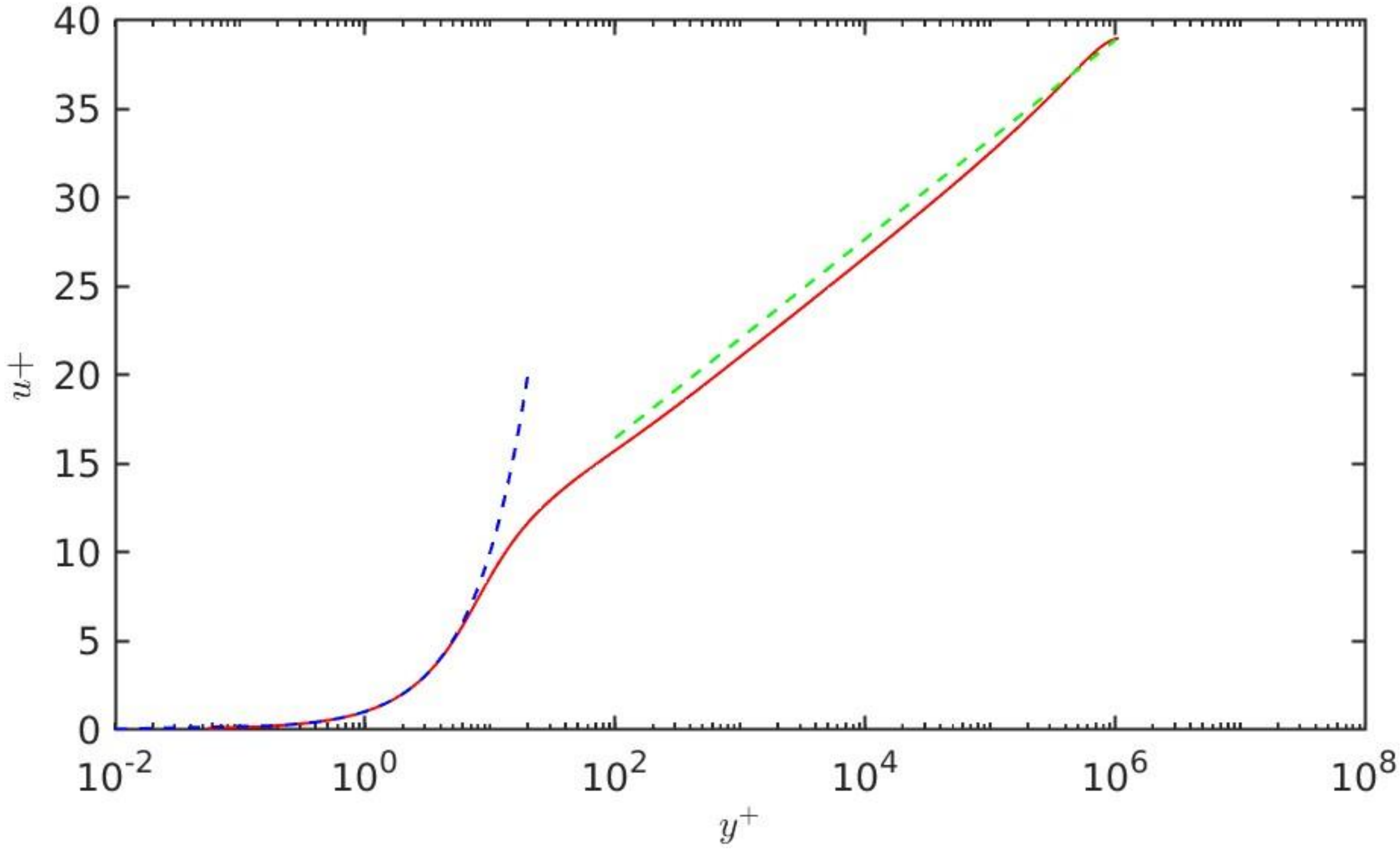
- Finest grid level
- 2nd order upwind for divergence of momentum, 1st order upwind for turbulence terms. Gauss linear scheme for Laplacians, gradients and cell to face interpolation



4) Channel flow results

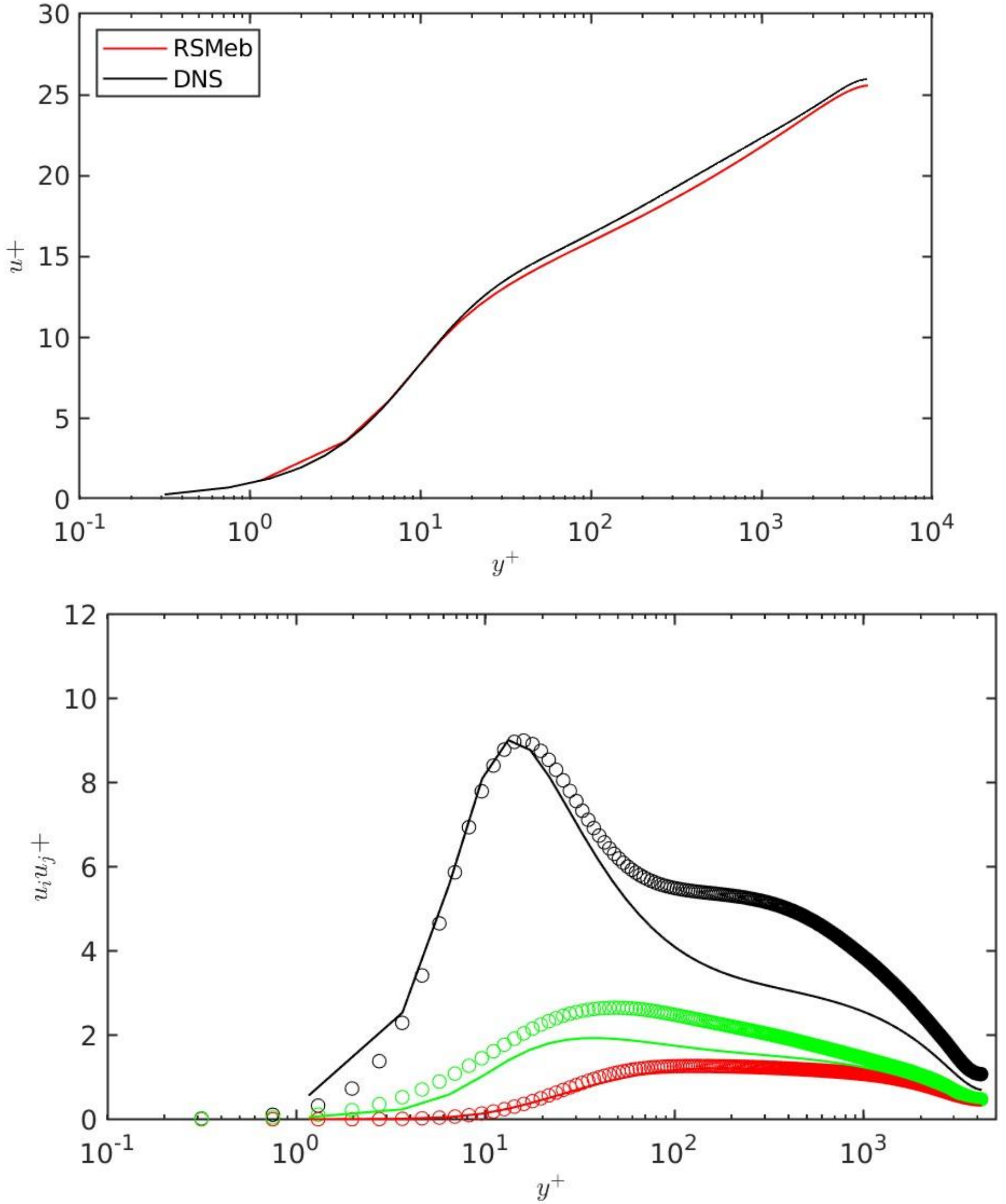
$Re = 8 \cdot 10^6$

- High aspect ratio problematic in OpenFOAM -> could not converge in parallel (tried different pressure solvers)
- Need to check if SST has the same problem



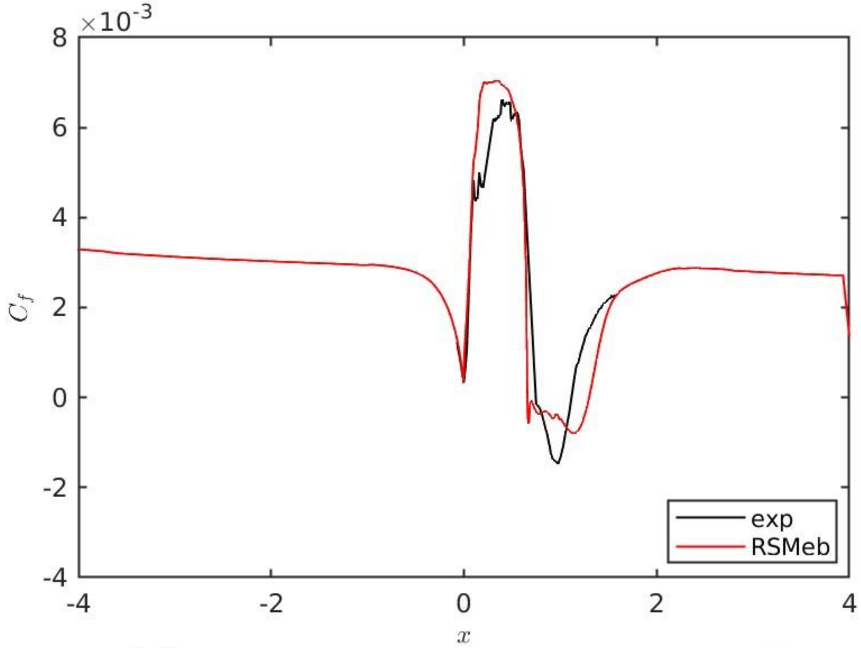
4) Channel flow results

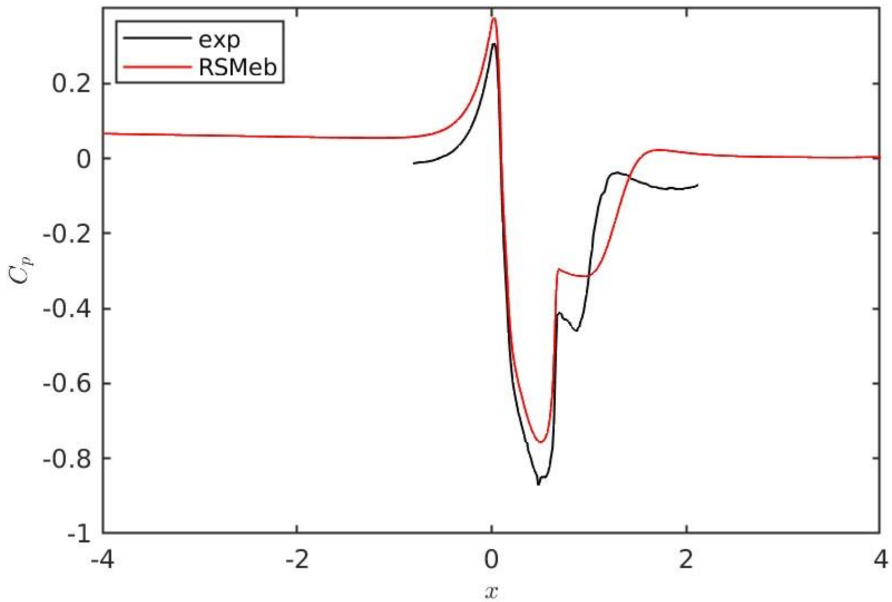
$Re_\tau = 4200$

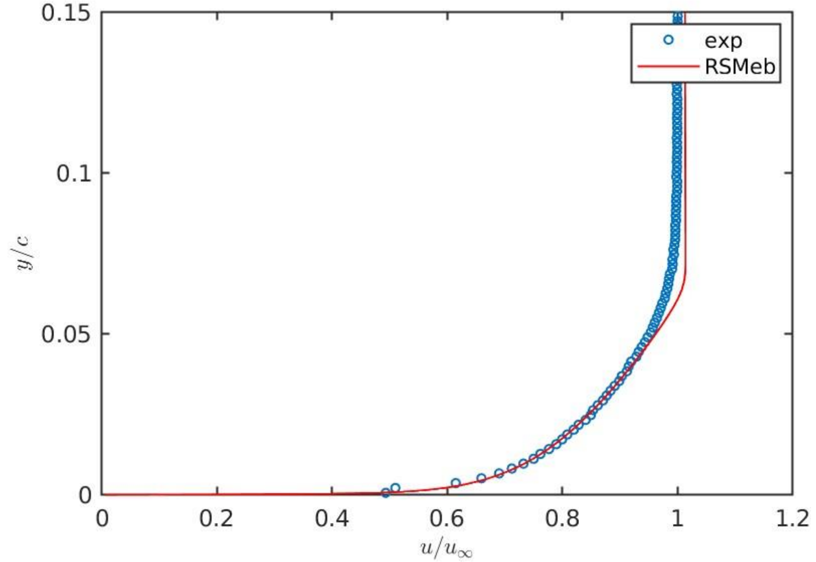


5) NASA Hump

Grid 817x217



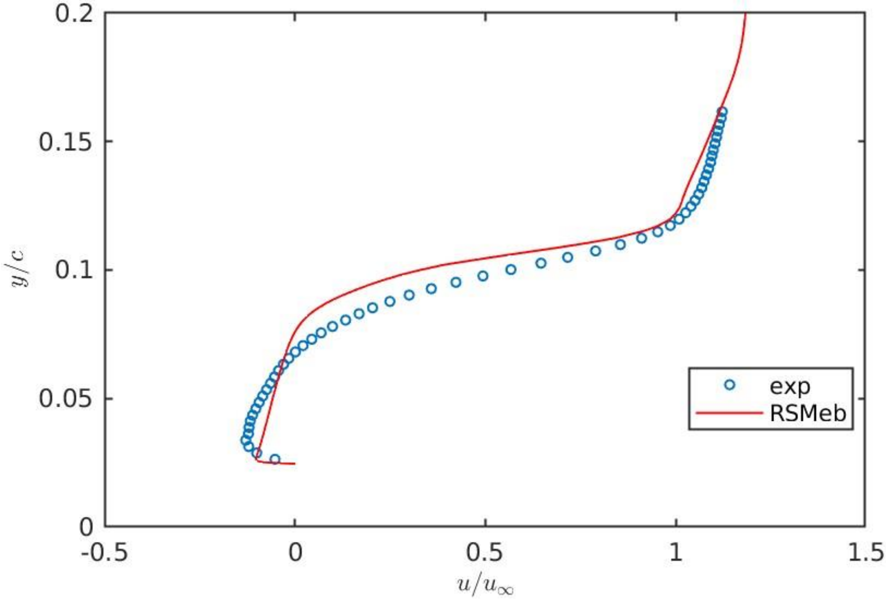




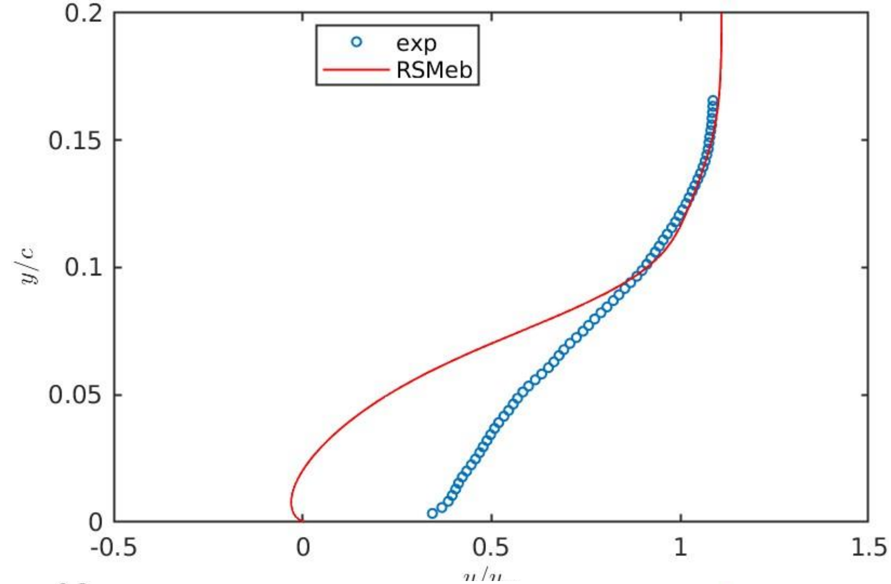
5) NASA Hump

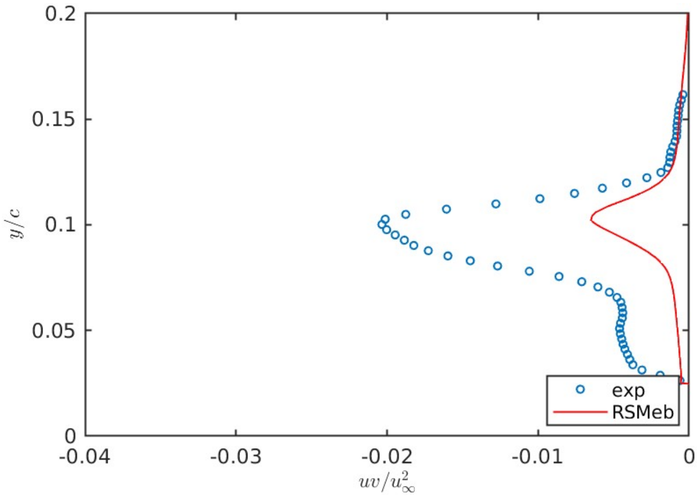
Grid 817x217

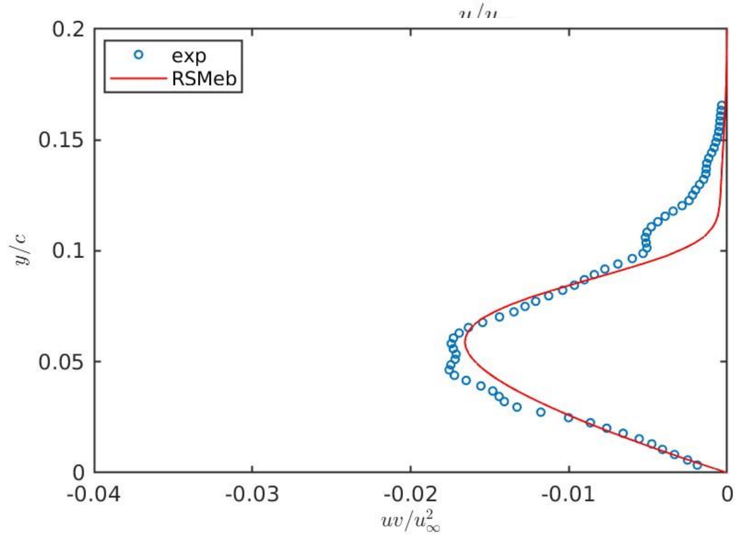
X=0.8



X=1.3

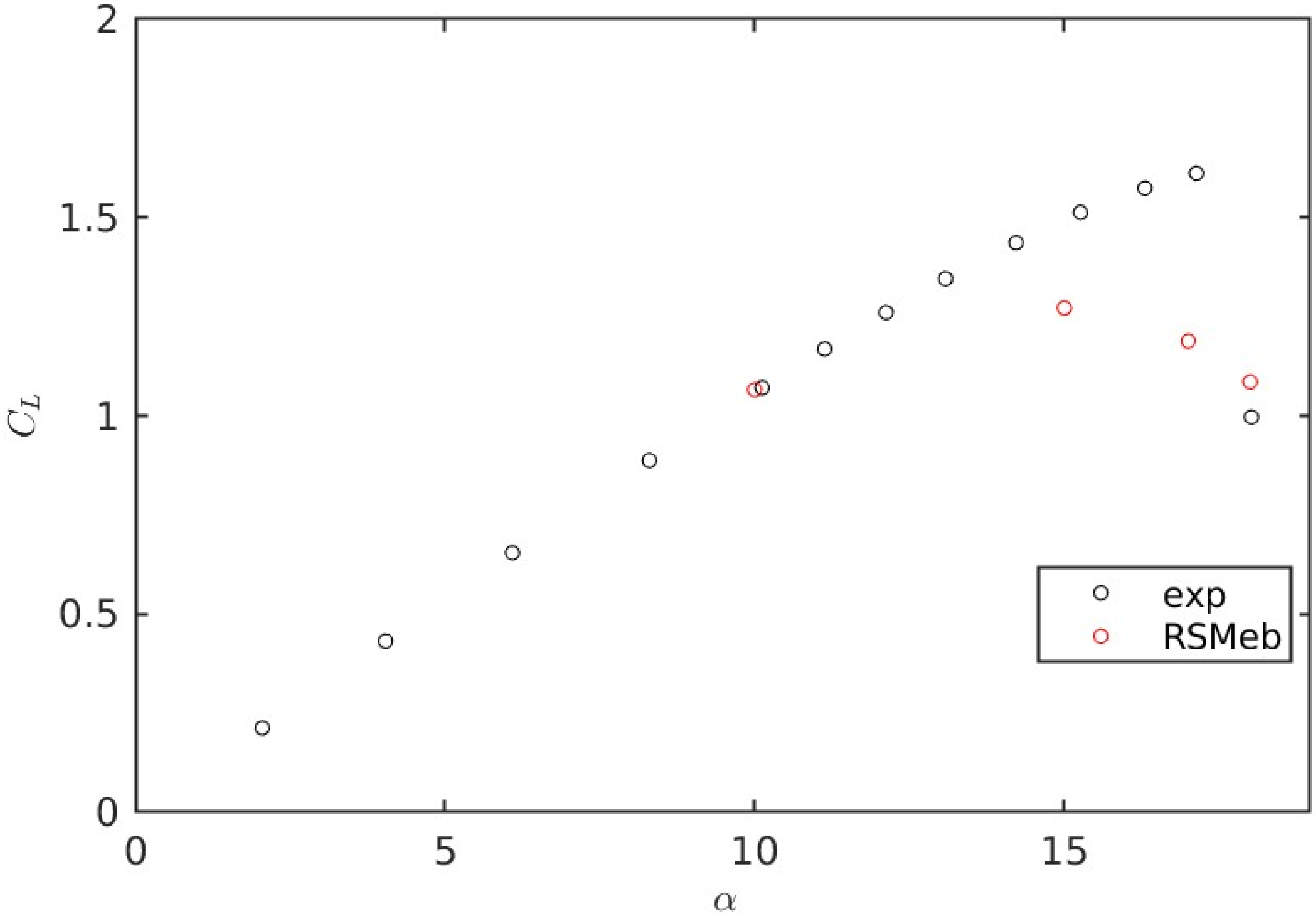






6) NACA 0012

Grid 897x257



Lessons learned

- Struggled with instability in axi-symmetric jet case
  - Had similar experience with RSM models in OpneFOAM when applied in 2d axi-symmetric reacting jet flows
  - Neil Ashton got the model to work thoughs in the rotating pipe cae
- More complex cases initialized with SST model results
- Having this suite of test-case (including several grid levels) is great to test the consequence of modifications to turbulence models in a broad range of flows very quickly (Allrun script takes a few hours on a desktop)
- The wide range of discretization scheme choices in OpenFOAM can be a curse
  - When observing stability problems, it is tempting to just use more “bounded” numerics that might affect the results significantly