V&V of DES using multiple CFD codes

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1) Strategy

- Use a basic two-equation type DES model implemented in different CFD codes: FUN3D, DLR-TRACE, OpenFOAM 6 (incompressible)
  - Main model complexity is in the RANS model with a simple length-scale based switch to LES
- Verify RANS model implementation by code comparison
  - TMR test case 2d bump in channel (low Mach) for grid convergence
  - 2d periodic hill at Re=37,000 (low Mach) (two grid levels)
- Verification of DES model by code comparison
  - 3d periodic hill at Re=37,000 (two grid levels)
- Validation of DES model by comparison to Experiment & WRLES
  - 3d periodic hill at Re=37,000

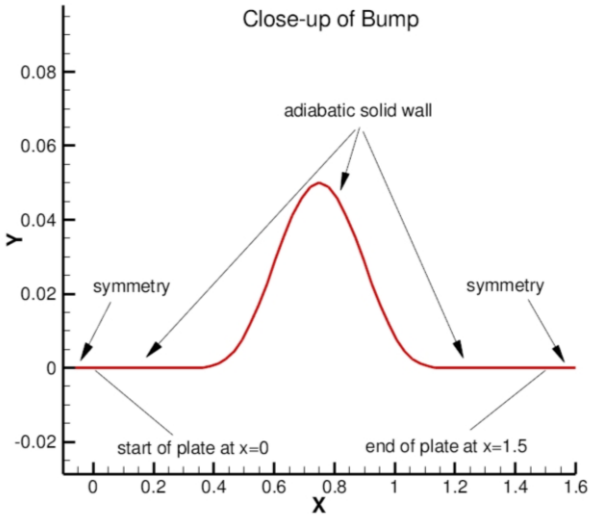
1) Strategy

- Use the Menter SST Two-Equation Turbulence Model from 2003 (M-SST-2003) (available in FUN3D)
- OpenFOAM v6 turbulence model ”kOmegaSST” is indeed the M-SST-2003 RANS model when using all default parameters
- The OpenFOAM ω boundary condition does not match the TMR description, we implemented a new BC
  - Removed “blended” BC branch
  - Removed the “log-law wall” check - only used “low-Re” formulation
  - ω_{wall} value is off by a factor of 10
- Near wall distance calculation in OpenFOAM differs from FUN3D

2) Pure RANS model verification

a) 2d-bump RANS verification

- TMR verification test case https://turbmodels.larc.nasa.gov/bump.html
- Low Mach number M = 0.2, Re = 3 million based on a length "1" of the grid
- Use TMR FUN3D results

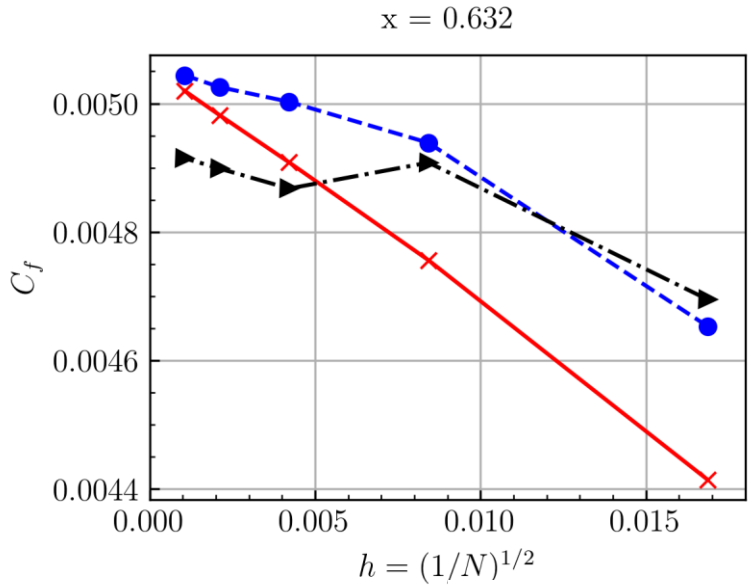


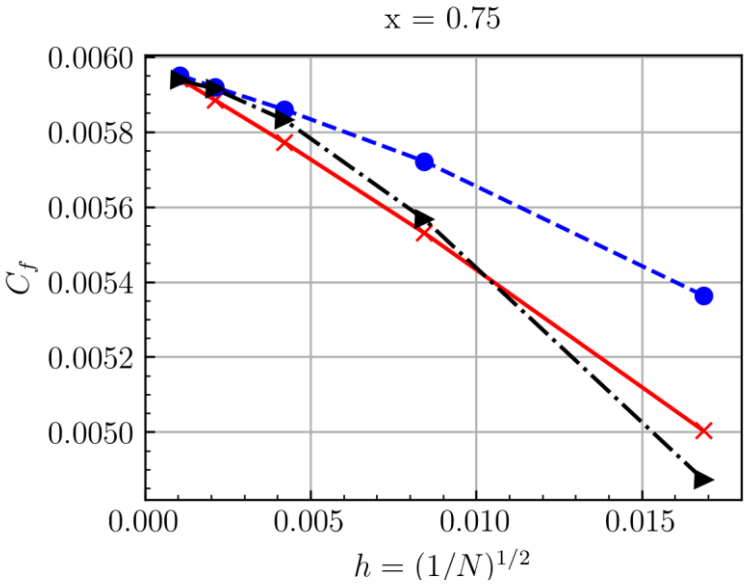
Numerical schemes

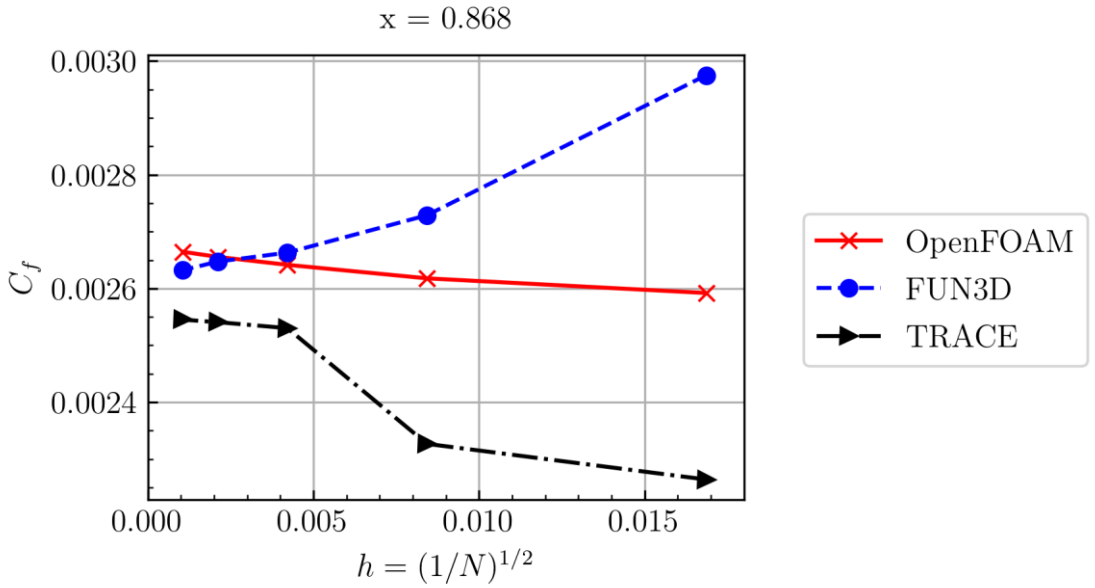
- OpenFOAM: 2nd Order upwind for divergence of momentum, 1st order upwind for turbulence terms. Gauss linear scheme for Laplacians, gradients and cell to face interpolation.
- FUN3D: The 2nd order unstructured-grid MUSCL scheme with an equal blend of upwind biased (Fromm) and cental difference discretization (κ = 0.5) in FUN3D. 1st order upwinding was used for the advective terms in the turbulence model.
- TRACE: 2nd order MUSCL scheme (κ = 0.0) for spatial discretization and 2nd order accurate central difference scheme was used for the viscous fluxes.

2) Pure RANS model verification

2d Bump grid convergence & code comparisons

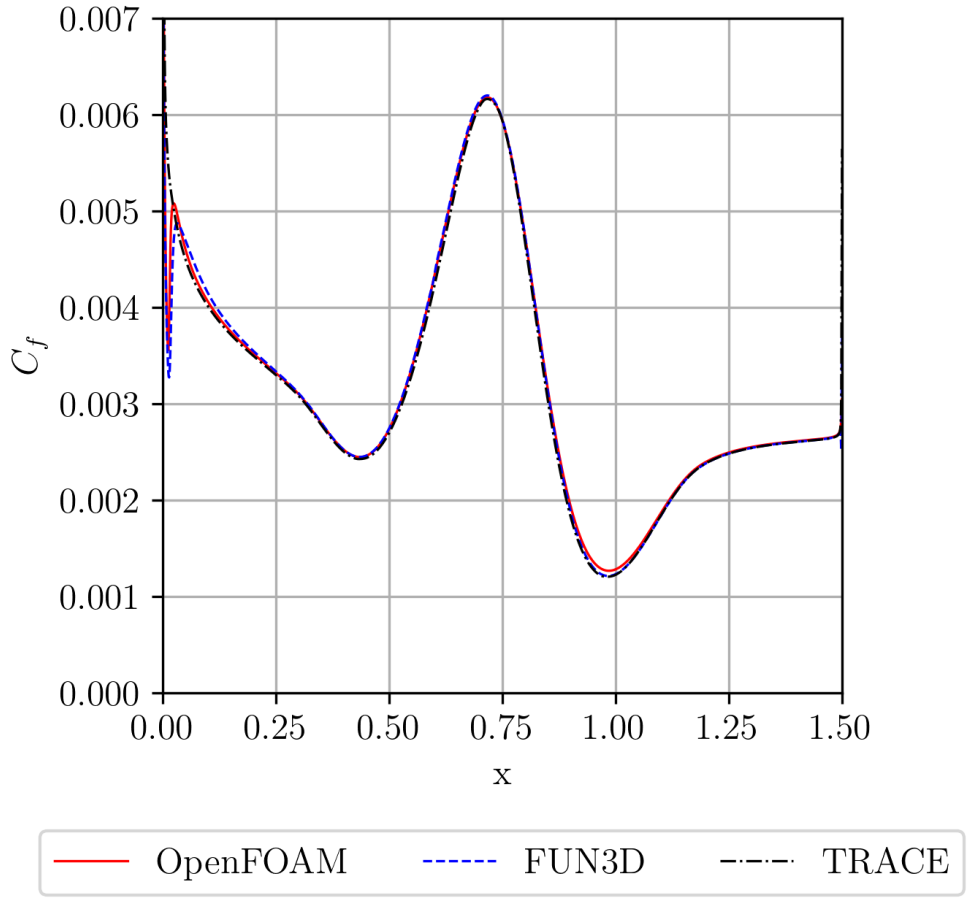






2) Pure RANS model verification

Code comparisons on finest grid 1409x641



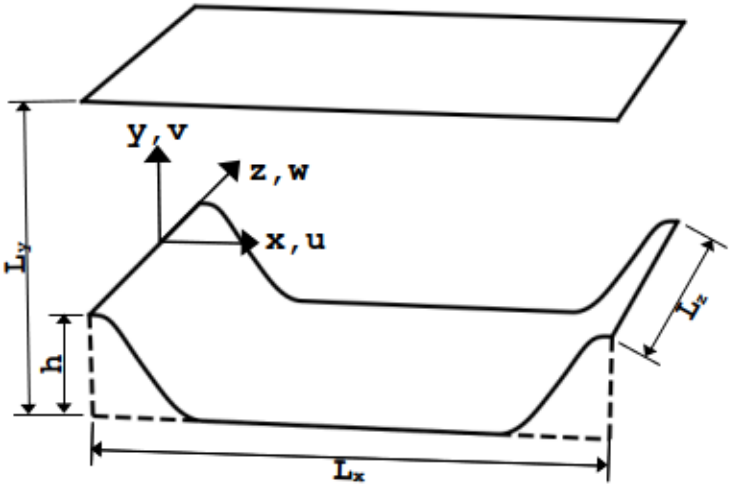
Codes	e_{rel}, C_f	e_{rel}, C_p	e_{rel}, μ_t
OpenFOAM-FUN3D	3.06%	2.01%	2.62%
OpenFOAM - TRACE	4.41%	1.89%	2.32%
FUN3D-TRACE	5.24%	1.92%	0.88%

2) Pure RANS model verification

- Overall FUN3D – OpenFoam closer than FUN3d – TRACE
- TMR comparison between FUN3D and CFL3D much closer than our results
- Initial studies show that Ma = 0.1 gets FUN3D – OpenFoam closer
- Consider switching to OpenFOAM v2206 (other branch) that has near wall distance calculation matching FUN3D (although wall near wall distance values are very close for the bump)
- Found a potential small bug in FUN3D (v 13.6) STT-2003 implementation
  - Strangely, there are two key-words for seemingly the same model: sst_2003 (used in TMR name list) and kw_sst_2003
  - The cross diffusion limiter of 10^{-10} is only used in kw_sst_2003 but in SST the "incorrect" 10^{-20} is used (subroutine ….)

2) Pure RANS model verification

b) Periodic Hill RANS verification



- Low Mach number - Ma = 0.1
- Except TRACE where Ma = 0.3.
- $Re = \frac{\rho_b U_b h}{\mu} = 37{,}000$ with $U_b = 1$, $\rho_b = 1$, and h = 1 at x=0
- $L_x = 9h$, $L_y = 3.035h$, and $L_z = 4.5h$.
- 200x100x1 grid generated in Pointwise and then exported to OpenFOAM, FUN3D, Trace

Numerical Scheme Changes in preparation for DES

- OpenFOAM: divergence scheme for velocity was switched to the "Gauss GammaV" scheme with gradients solved using a "cellLimited leastSquares"

2) Pure RANS model verification

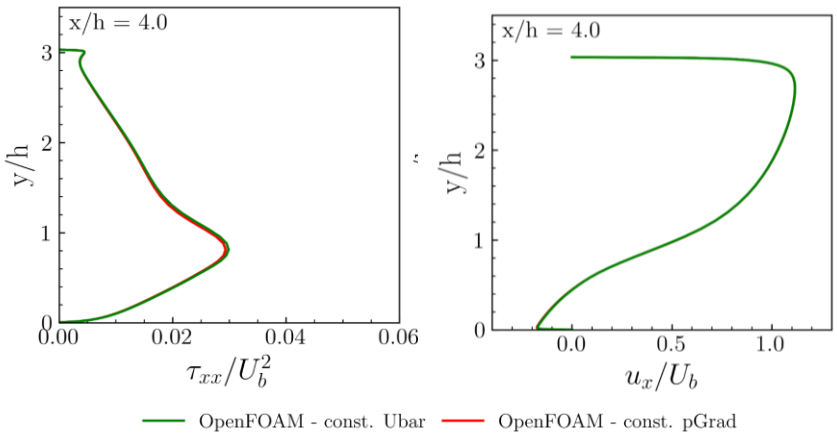
Forcing of the periodic flow

- Two options for driving the periodic flow: **constant volume averaged velocity:**

$$\bar{U} = \frac{V}{V_c} \cdot U_b = \frac{114.2m^3}{9m \cdot (3.035m - 1m) \cdot 4.5m} \cdot 1m/s = 0.721m/s,$$

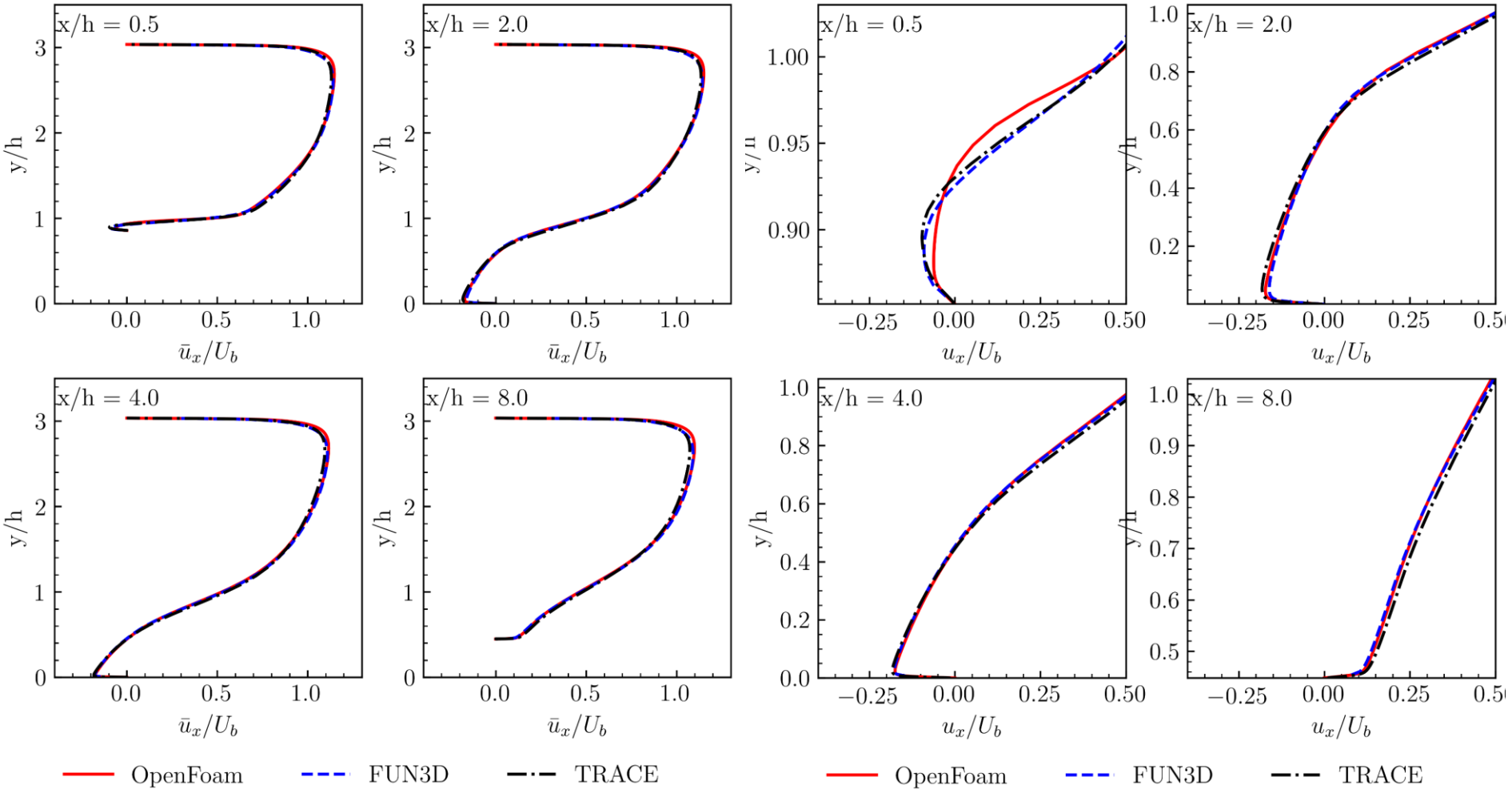
and **constant axial pressure gradient.**

- Used a constant $\overline{U}$ case to determine the pressure gradient with OpenFOAM => $\frac{dp}{dx} = 6.326 \cdot 10^{-3}\ Pa/m$
- Decided to use a constant pressure gradient as there is no volume averaged velocity momentum source in FUN3D
- TRACE results from const. vel. forcing!



RANS results essentially unaffected by driving force method!

2) Pure RANS model verification

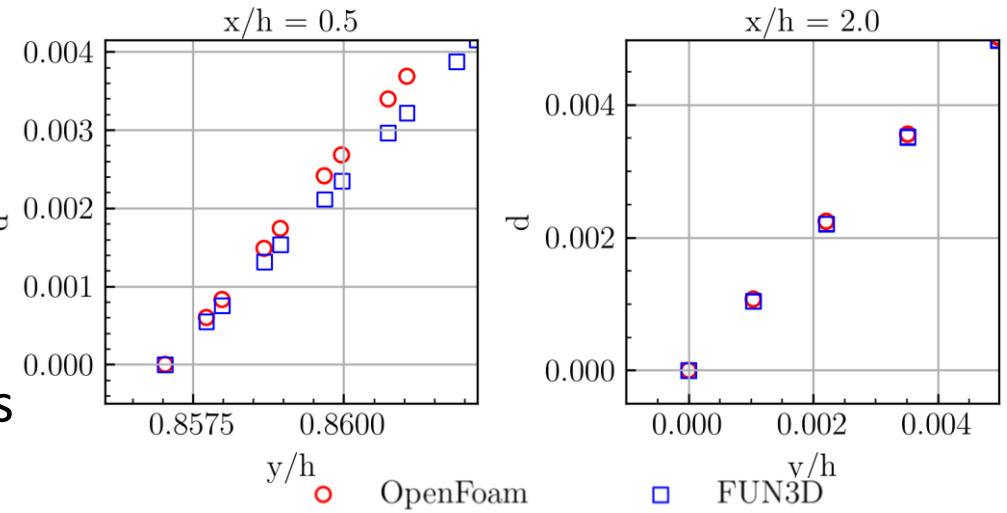


- Bulk velocity at x=0: $OF = 0.999$, $FUN3D = 0.985$ (should be = 1)
- Relative difference OF-FUN3D largest at x/h=4 with 5.8% (FUN3D-Trace =5.2%)

2) Pure RANS model verification

Explanations for larger differences than in bump

- Used a coarser grid
- Difference in near wall distance calculation
- Difference in numerical schemes



Next steps

- Use OF v2206 and check near wall distance
- Use a twice finer 400x200 grid
- Carefully check if we can match discretization schemes closer

3) DES model Verification

DES modification of M-SST=2003

TKE dissipation

$$D^k_{RANS} = \beta^* \rho \omega k = \frac{\rho k^{3/2}}{l_{k-\omega}} \qquad l_{k-\omega} = \frac{k^{1/2}}{\beta * \omega}$$

Changed to

$$D^k_{DES} = \frac{\rho k^{3/2}}{\tilde{l}}. \qquad \tilde{l} = min(l_{k-\omega}, C_{DES}\Delta)$$

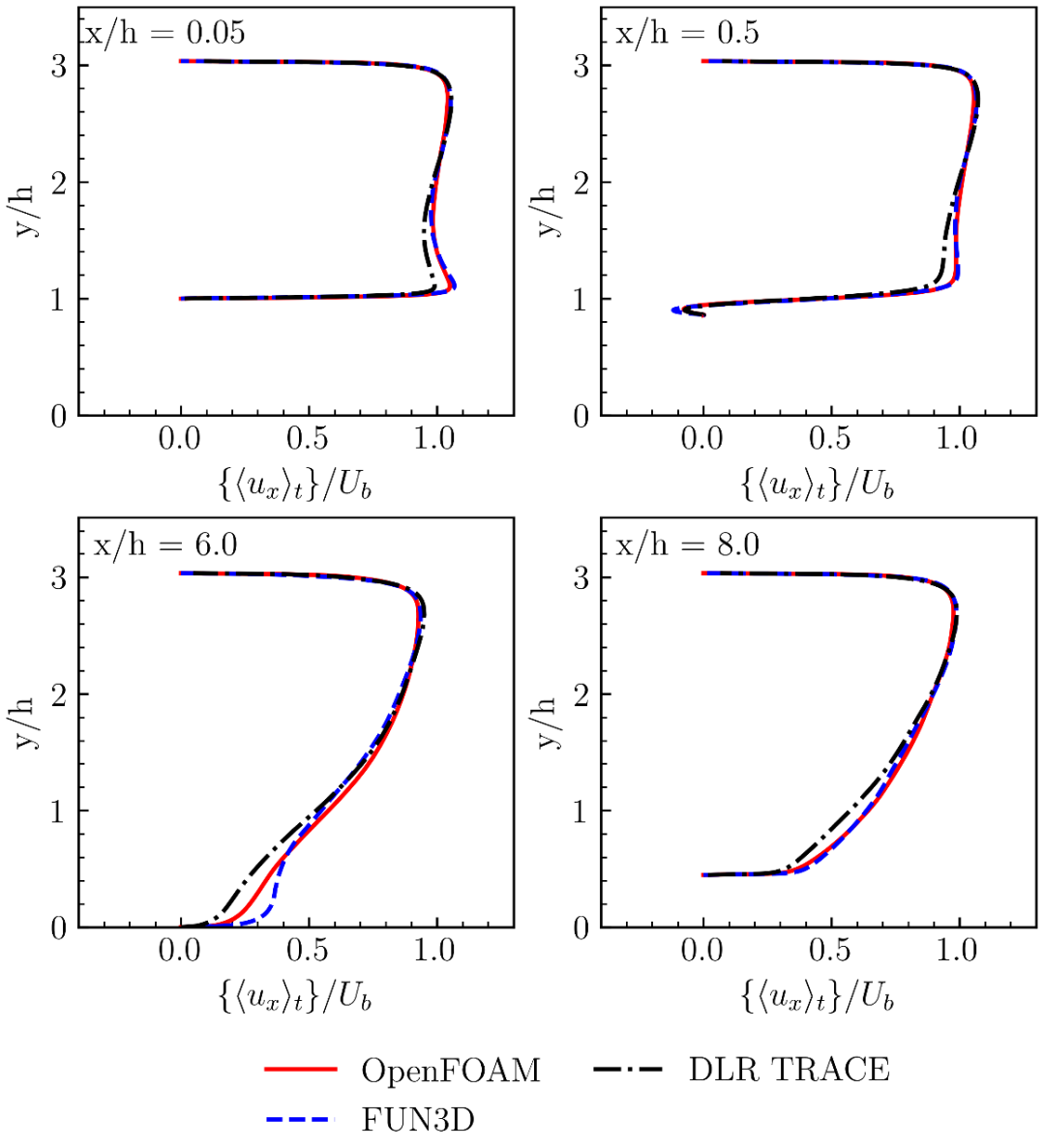
$$C_{DES} = (1 - F_1)C^{k-\epsilon}_{DES} + F_1(C^{k-\omega}_{DES}) \qquad C^{k-\epsilon}_{DES} = 0.61 \text{ and } C^{k-\omega}_{DES} = 0.78$$

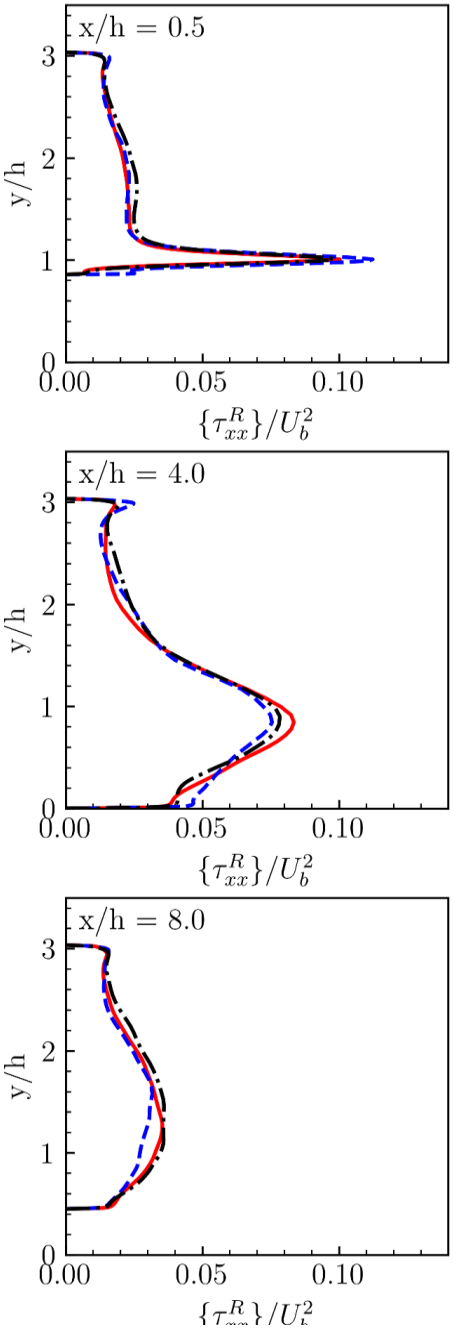
- Used different FUN3D DES model first: “des_kw_sst” + “strelets_des = .true => suspect an implementation error (tke production and dissipation multiplied by rho in non-conservative implementation?)
- Implemented new FUN3D model “des_sst_2003” (lot’s of copy and pasting of the RANS model source code)
- Basic Verification: using “strelets_des = .false.” in “des_sst_2003” reverts it back to pure RANS “sst_2003” and results are identical

3) DES model Verification

- Grid 200x100x100 (same 200x100 grid extruded into spanwise direction suing 100 cells)
- OpenFOAM and FUN3D used $\Delta t/t_c$ = 11.11 x 10^{-4}, TRACE used $\Delta t/t_c$ = 13 x 10^{-4} => time averaging requirement > $20t_c$
- Fixed driving pressure gradient determined from OpenFOam and then non-dimensionalized $\frac{dp^*}{dx^*} = 1.0638 \cdot 10^{-5}$ (FUN3D), TRACE ($Ma = 0.3$) results still based on const. bulk velocity driving!
- FUN3D needs full sub-iteration convergence (followed “unsteady tutorials”) => typically 15 sub-iterations required
- FUN3D is about 7x more costly than OpneFOAM
  - Used 4x larger time step (thanks to fully implicit) to catch up
  - Ran out of time: results averaged only over $\sim 10t_c$
- Check bulk velocity: $U_{b,OF} = 1.057$, $U_{b,FUN} = 1.037$

3) DES model V&V





4) Conclusions and next steps

- Verification for RANS
  - 2d-bump-in-channel case at $Ma = 0.2$ => overall ok but try to get it closer
  - Periodic hill flow case at $Ma = 0.1$ => finer grid results needed
- Verification for DES, periodic hill flow case at $Ma = 0.1$
  - Probably need $30 - 50\ t_c$ for time averaging + spatial averaging (could not get FUN3D's built-in tool to work)
  - FUN3D results need more time to run => keep using larger time step to speed up
  - Grid convergence study: run a 8x finer grid (16M cells) but with $\Delta_{fine} = \Delta_{coarse}$ (need to hack FUN3D model)
- Validation for DES
  - Easy, just compare with WRLES and experiments (OF results look very reasonable)

Thank you to

- Chris Rumsey, Gary Coleman, Mary Bunde and all others to make this workshop happen
- My collaborators
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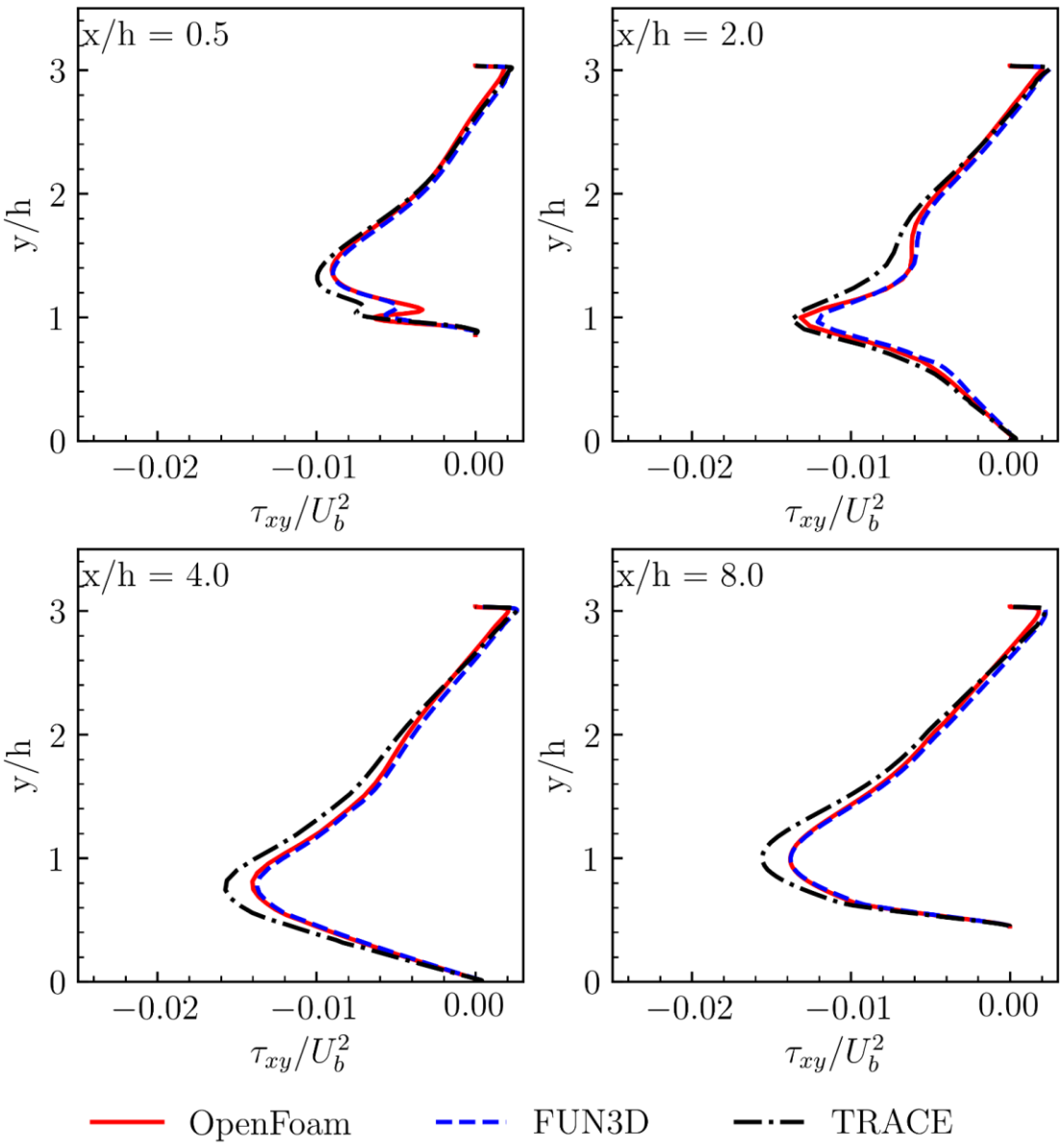
- UWYO-ME for TA support of Jorden
- You all for listening

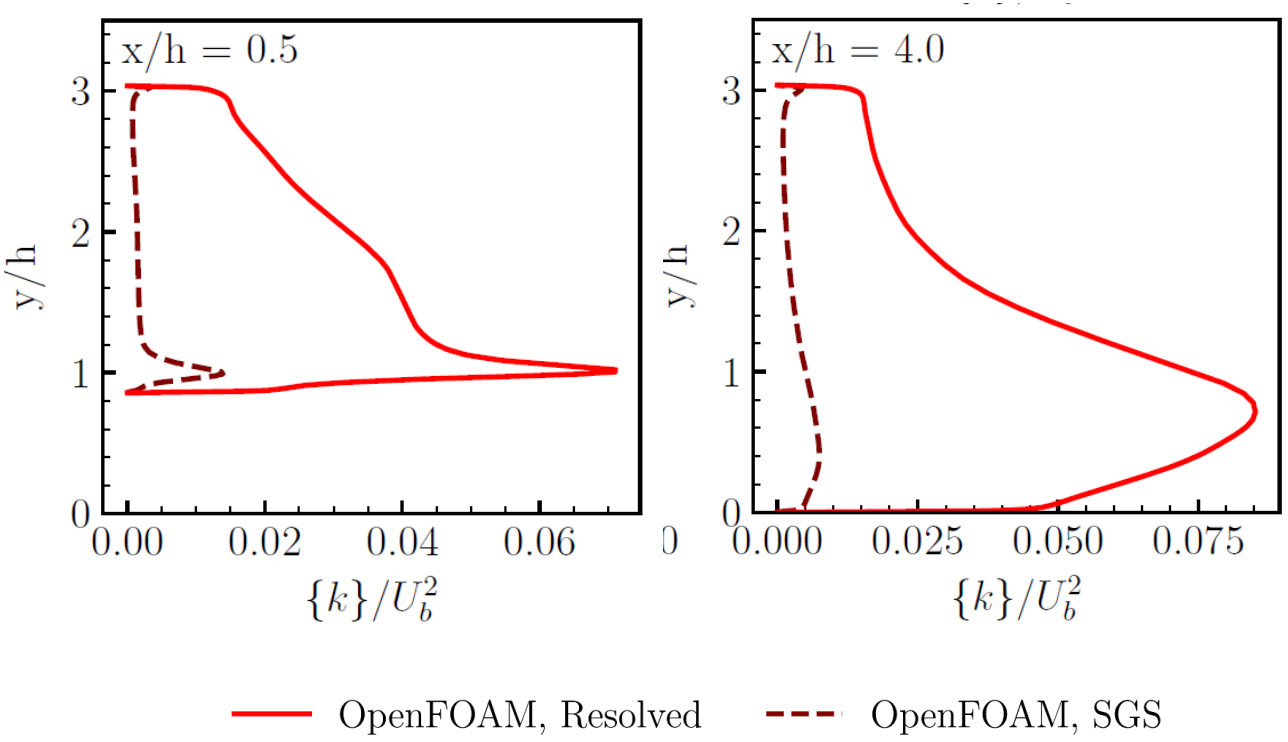
2) Pure RANS model verification



Relative difference OF-FUN3D for τ_{xy} largest at x/h=0.5 with 12.7%

3) DES model V&V

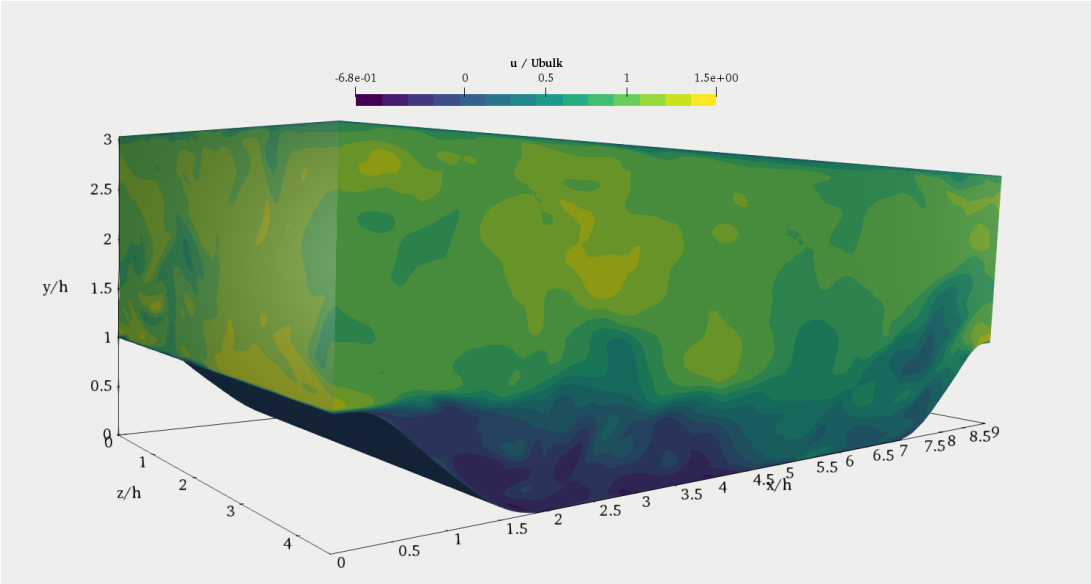
OpenFOAM tests



As expected, modeled contribution only significant near the walls

3) DES model V&V

OpenFOAM time-averaging results

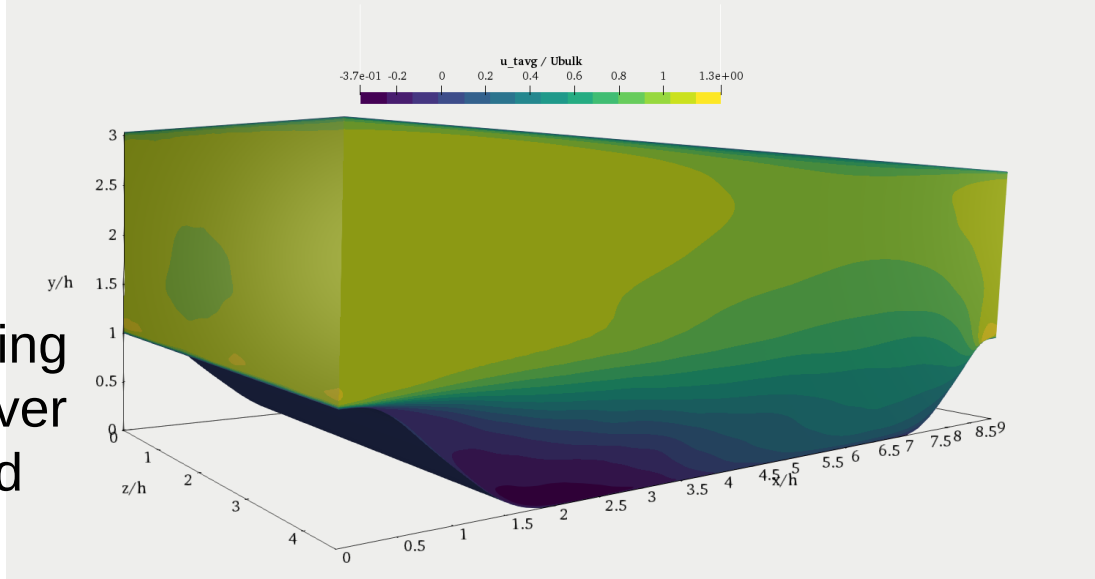


Instantaneous velocity at $t = 32.5t_c$

Mean velocity (averaged over $20t_c$)

Not perfectly symmetric!

- would need longer time averaging
- Instead, additional averaging over the 100 spanwise points is used



3) DES model V&V

K-w, Ub_of=1.057, Ub_fun=1.0392