Recent Developments on the Turbulence Modeling Resource Website

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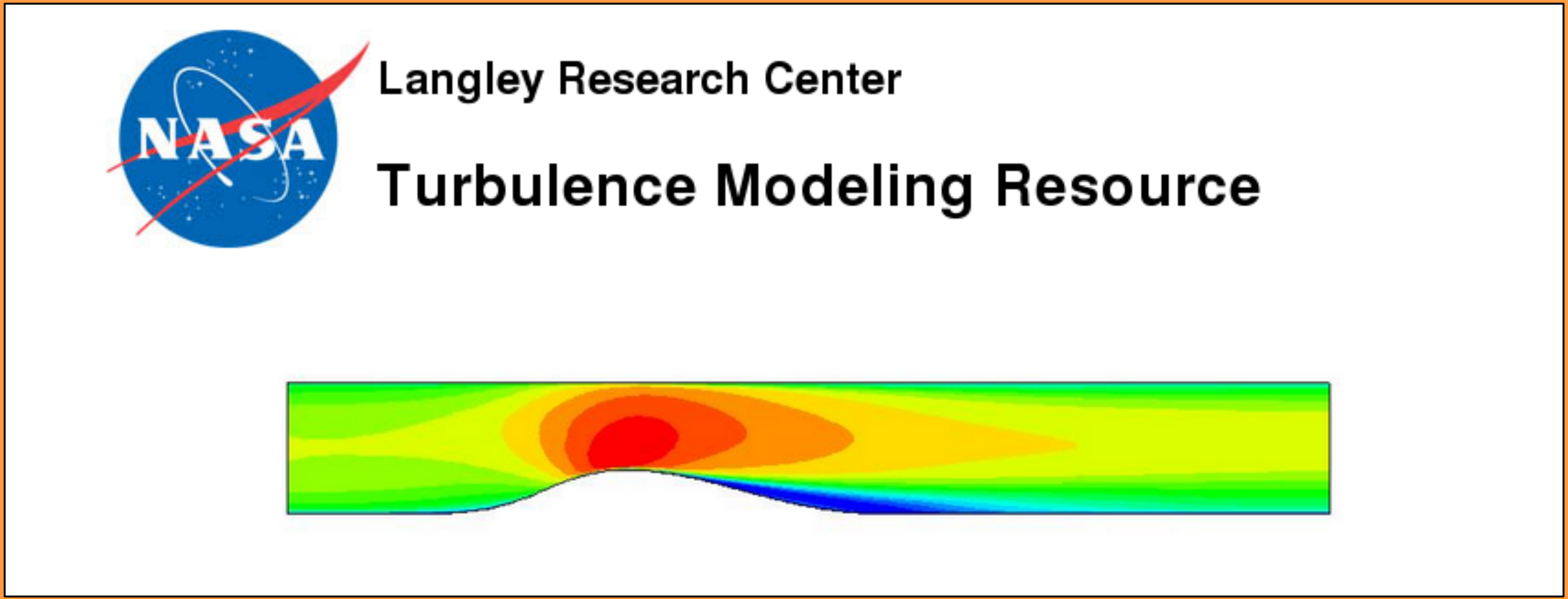
NASA LaRC

Outline

- Introduction
- Turbulence Modeling Resource (TMR) Main Features
  - General overview, with some focus on newer material
- Summary, Future Plans, Open Questions



Introduction

- Turbulence models are required to close the Reynolds averaged Navier-Stokes (RANS) equations
- Validation is always required, but…
- Validation is not helpful without verification
  - Rarely done, e.g., method of manufactured solutions (MMS)
  - "Verification by comparison" may be next best thing (but must include grid convergence studies!)
  - "Aha! Moment" from a turbulence modeling workshop in 2005
- Other turbulence modeling Verification & Validation (V&V) issues:
  - Boundary conditions can matter
  - Need for easy availability of experimental & LES/DNS data
  - Numerical issues associated with turbulence models
  - There is often confusion regarding the version of the turbulence model being used (see, e.g., Viti, Huang, Bradshaw (2007))
- TMR tries to address all of this
- Associated with the Turbulence Model Benchmarking Working Group (TMBWG), under AIAA's Fluid Dynamics TC

Viti, Huang, Bradshaw (2007)*

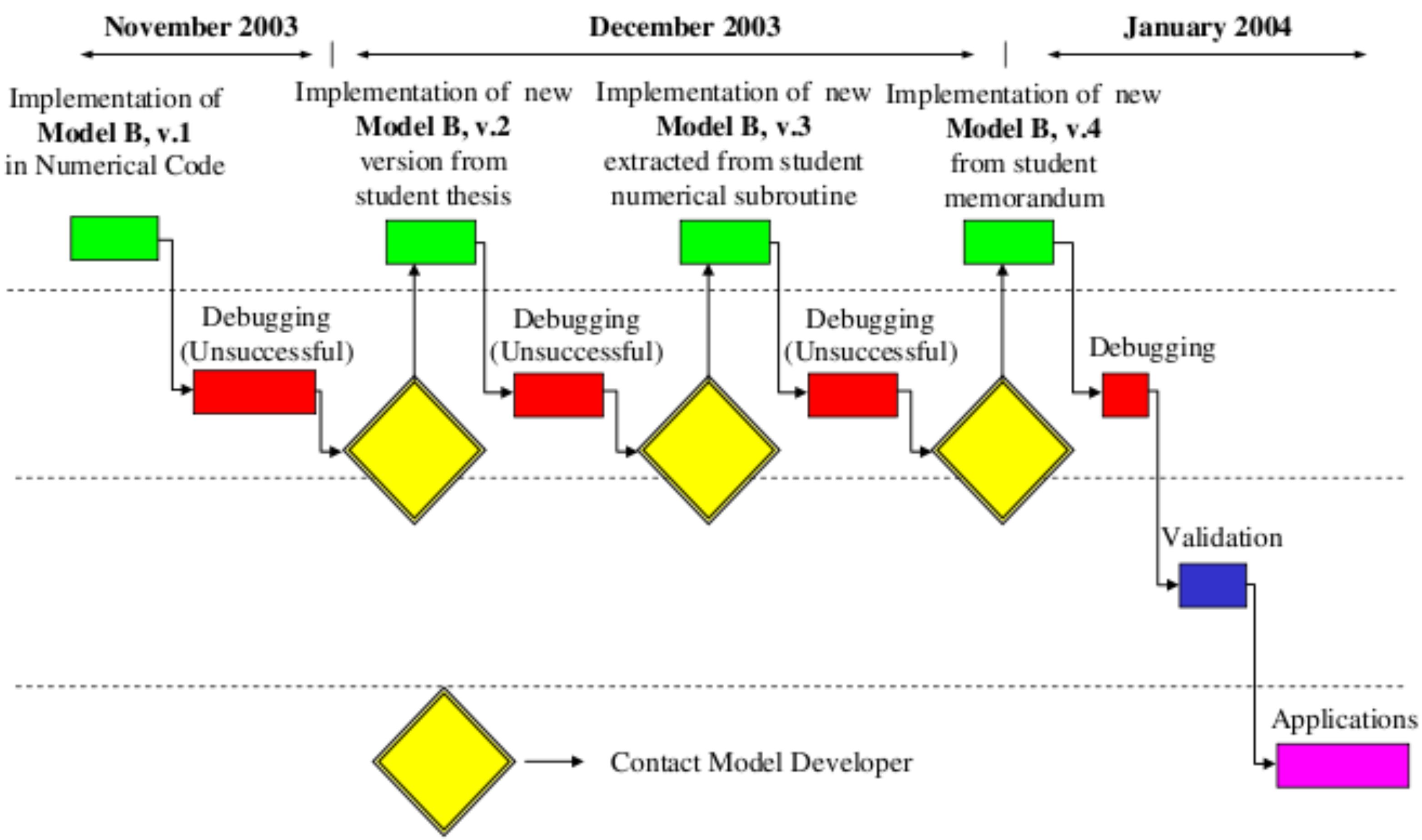


*Figure from Computers & Fluids 36 (2007) 1373-1383

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Description of Turbulence Models

Turbulence Models

- One-Equation Models:
  - Spalart-Allmaras
  - Nut-92
- Two-Equation Models:
  - Menter k-omega SST
  - Menter k-omega BSL
  - Wilcox k-omega
  - Chien k-epsilon
  - K-kL
  - Explicit Algebraic Stress k-omega
- Three-Equation Models:
  - K-e-Rt
- Seven-Equation Omega-Based Full Reynolds Stress Models:
  - Wilcox Stress-omega
  - SSG/LRR
- Seven-Equation Epsilon-Based Full Reynolds Stress Models:
  - GLVY Stress-epsilon

(Guidelines for submitting a new turbulence model description: Guideline-turbmodeldescription.pdf)

Implementing Turbulence Models into the Compressible RANS Equations

Notes on running the cases with CFD

Currently 12 different models described, plus variants;
defines NAMING CONVENTIONS

New models can be added, with input from model developer(s)

V&V currently not done for all models, due to limited resources

Verification Cases

Implementing Turbulence Models into the Compressible RANS Equations

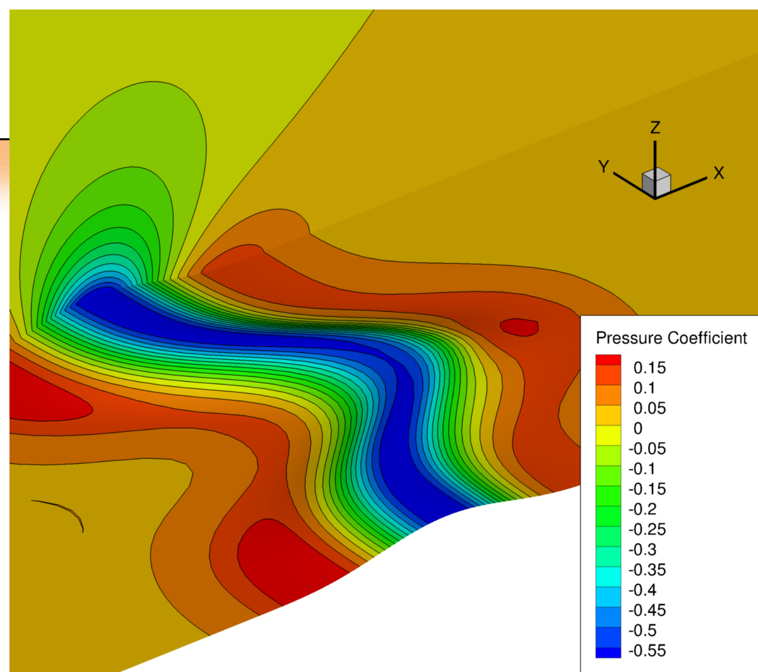
Notes on running the cases with CFD

Turbulence Model Verification Cases and Grids

- 2D Zero pressure gradient flat plate
- 2D Planar shear
- 2D Bump-in-channel
- 3D Bump-in-channel

Same 4 have been here from the beginning

All grids are provided

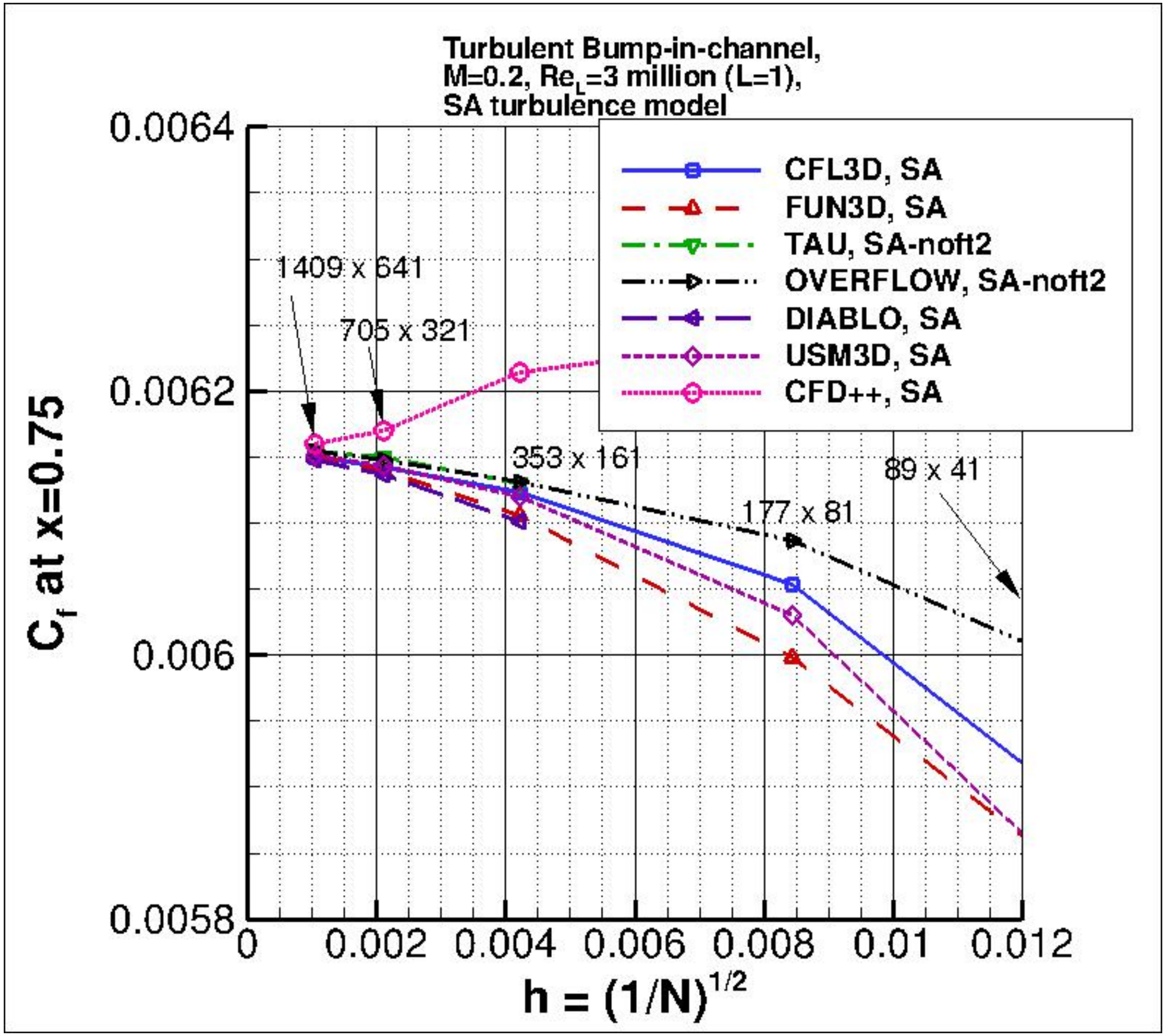


3-D Bump-in-channel verification example, using Wilcox2006 model

Verification Cases

- "Verification by comparison" is not fool-proof
  - Sufficient iterative convergence is very important!
  - 2 (or more) codes may have similar errors, or particular errors may not show up for the cases considered
  - But the more codes that agree, and the more cases we do, the more confidence we have
  - Transparency and openness of TMR allows the whole world to check its accuracy (and tell us if a problem or inconsistency is found)
- Model Readiness Rating (MRR) system
  - 0=no results yet; model description only
  - 1=model only in one code on TMR
  - 2=two or more codes agree on at least two cases on TMR
  - 3=two or more codes from different organizations agree on TMR (independently obtained)

Verification Cases



Example of a turbulence model (SA) with MRR Level=3

We have very high confidence in the SA results on the TMR – users can trust these results

Models with MRR Level=3 currently:

-SA

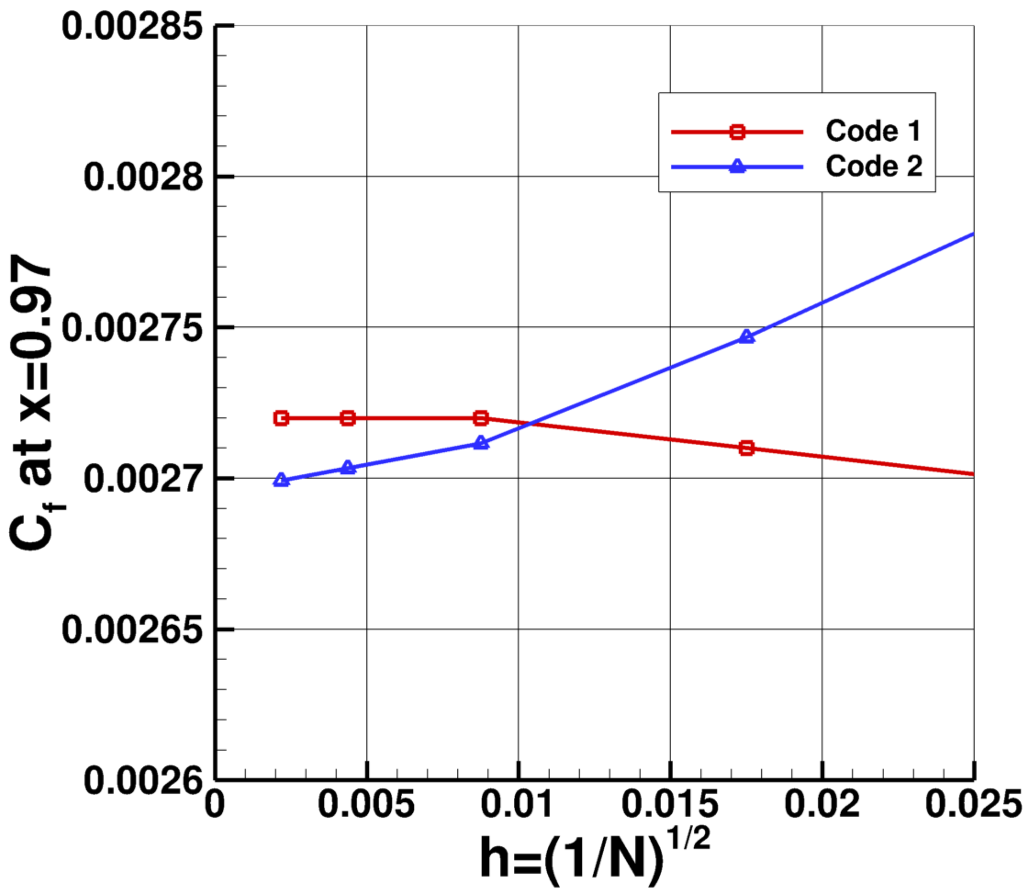
-SST

-SST-V

-SSG/LRR-RSM-w2012

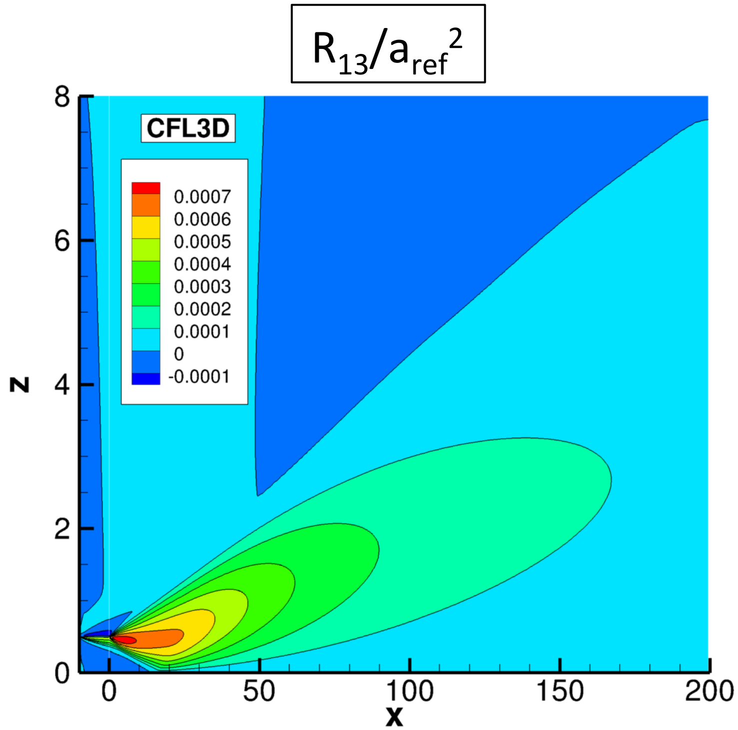
Verification Cases

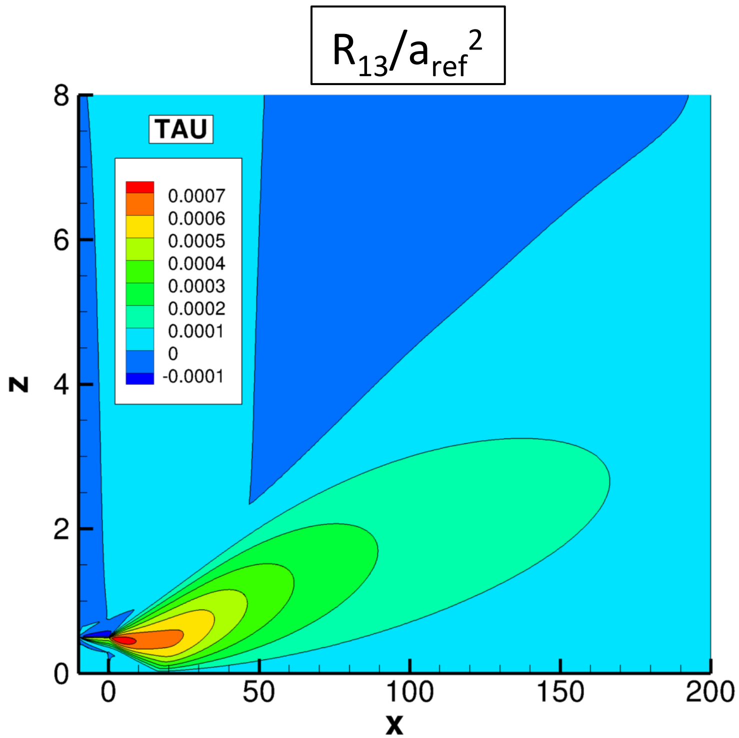
Example of a turbulence model NOT posted, as "verification by comparison" has not yet been successfully achieved



"Visual Richardson extrapolation"

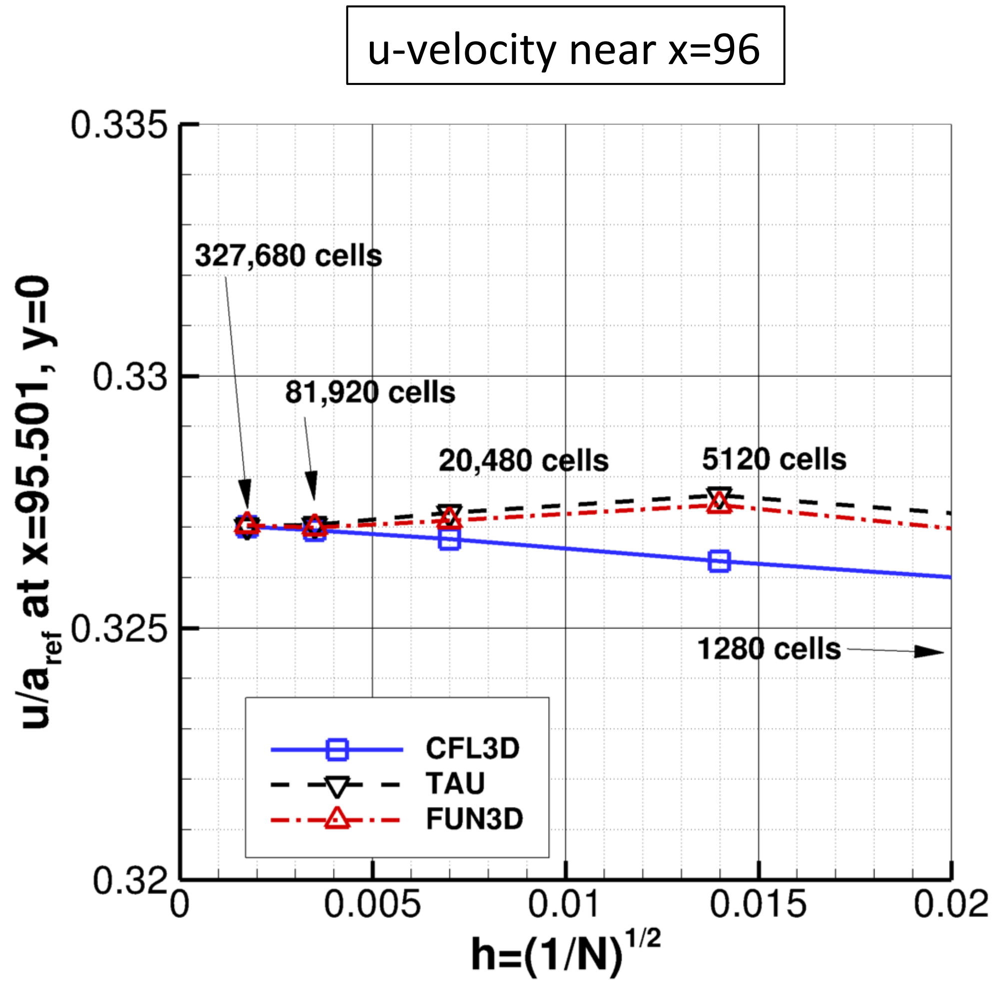
Verification Cases – recently added





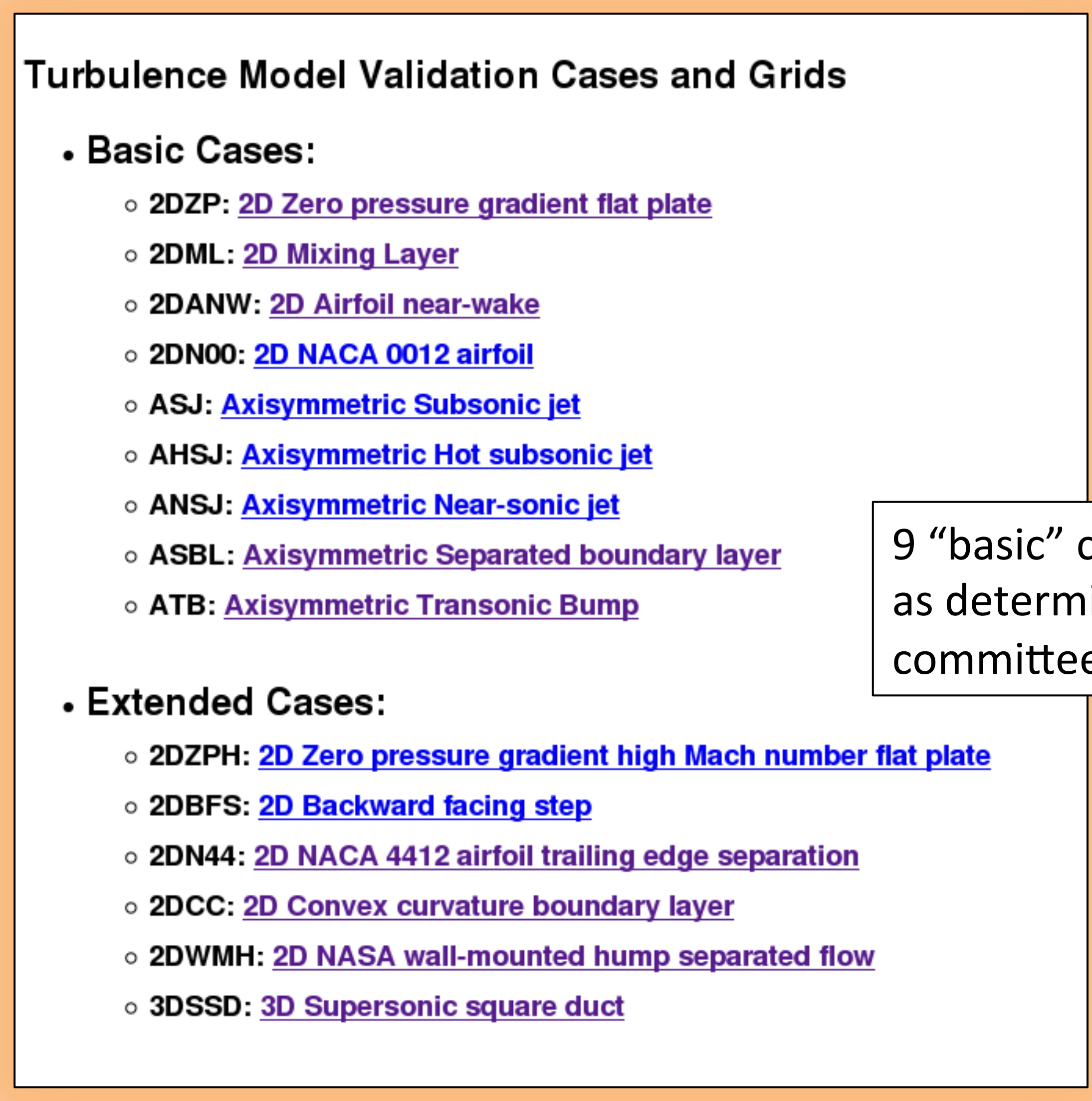
- SSG/LRR-RSM-w2012 7-eqn model has recently been added to 3 of the 4 verification cases
- Above is example from 2-D planar shear case
- All turbulence quantities are nearly identical (on finest grid) between different codes

Verification Cases – recently added



Although various codes are not always consistent in terms of order properties, global quantities approach nearly the same answer as grid is refined

Validation Cases



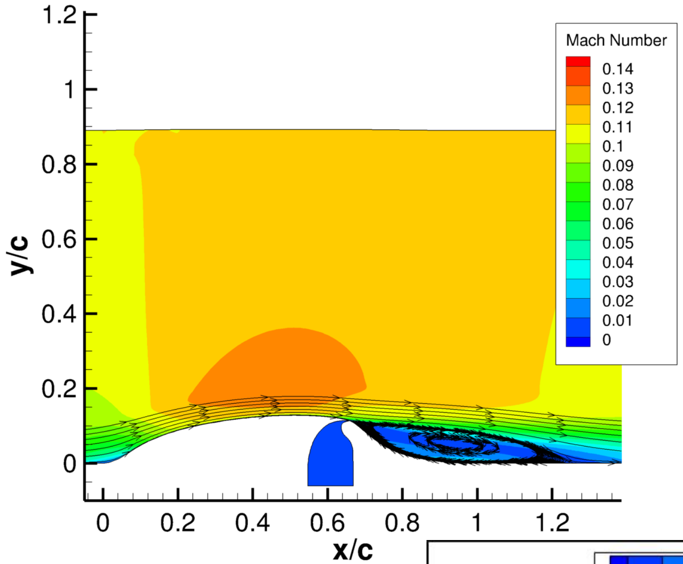
9 "basic" cases and 6 "extended" cases, as determined by the TMBWG committee

Validation Cases

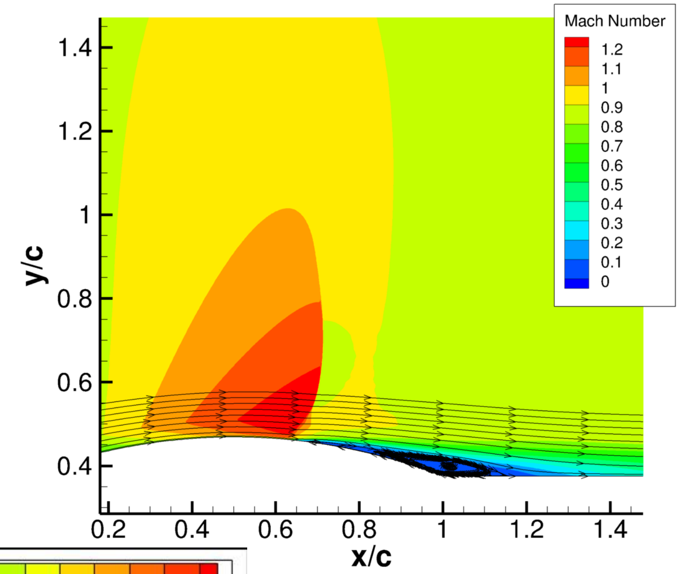
		Free shear flows			Wall flows		P-gradients	Curv-ature	Compressibility			Secon-dary flows	Turb Heat Flux	Higher Mach	Vortex flows	Separa-tion
		Jet Anomaly	Mixing layers	wakes	Law of wall	Law of wake			Mixing	Van Driest I	Van Driest II					
Boundary Layers	2DZP															
	2DZPH															
	ASBL						weak									weak
Mixing layer/ wakes	2DML															
	2DANW															
Jets	ASJ															
	ANSJ															
	AHSJ															
Airfoils	2DN00															weak
	2DN44															
Bump flows	ATB															
	2DWMH															
Internal flows	2DCC															
	2DBFS						strong									
	3DSSD															

Validation Cases – recently added

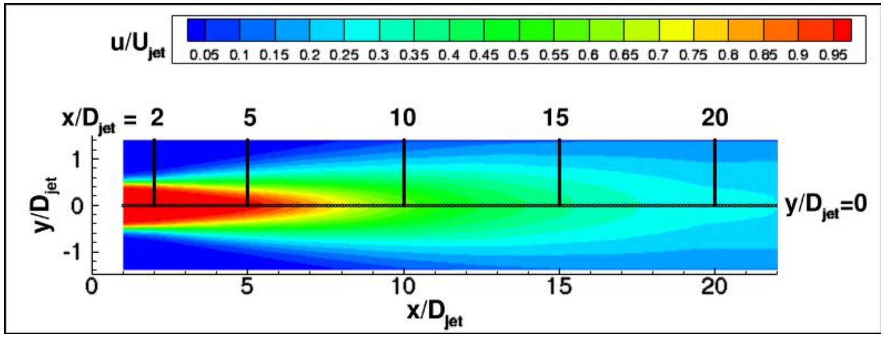
2DWMH Case



ATB Case



AHSJ Case*

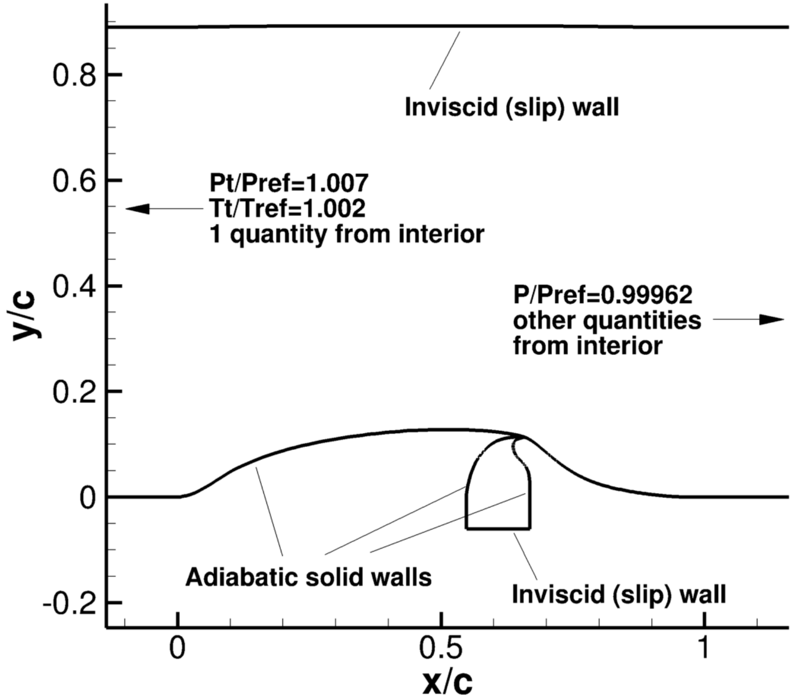


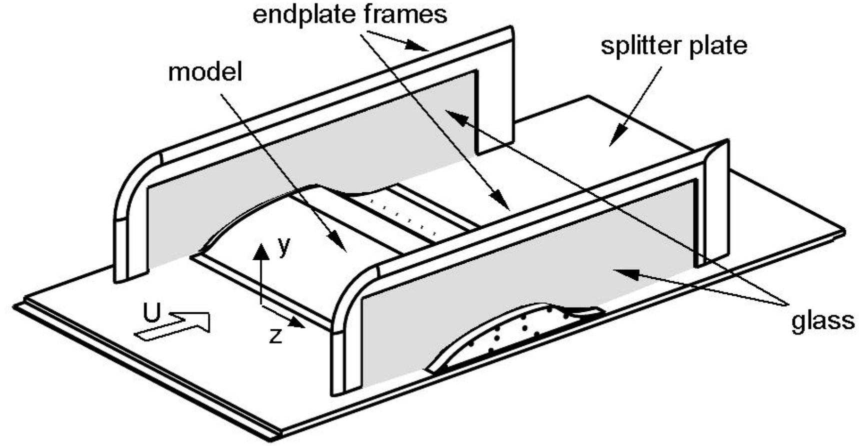
* = added after this paper was written

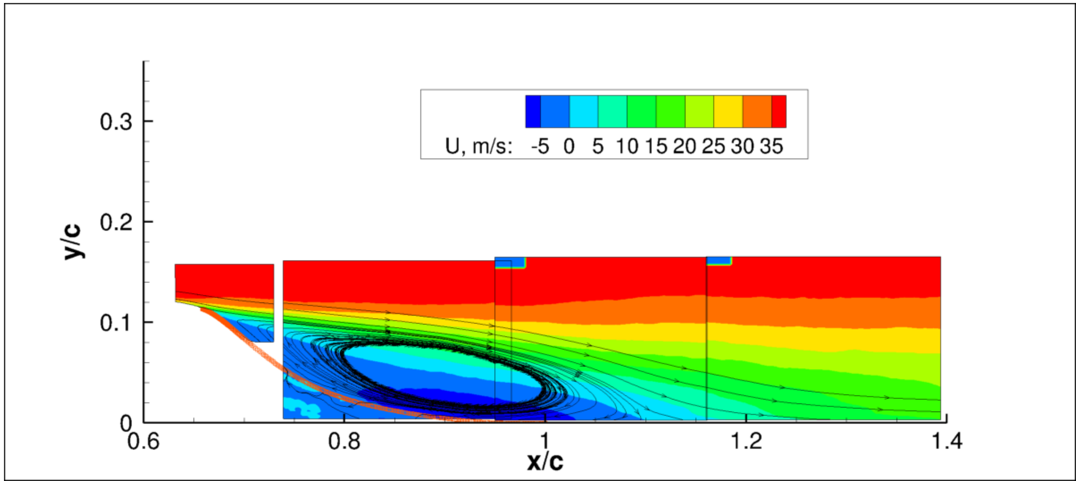
These cases are three of the configurations considered for NASA's "40% Challenge":

Identify and down-select critical turbulence, transition, and numerical method technologies for 40% reduction in predictive error against standard test cases for turbulent separated flows, evolution of free shear flows and shock-boundary layer interactions on state-of-the-art high performance computing hardware.

2DWMH Validation Case

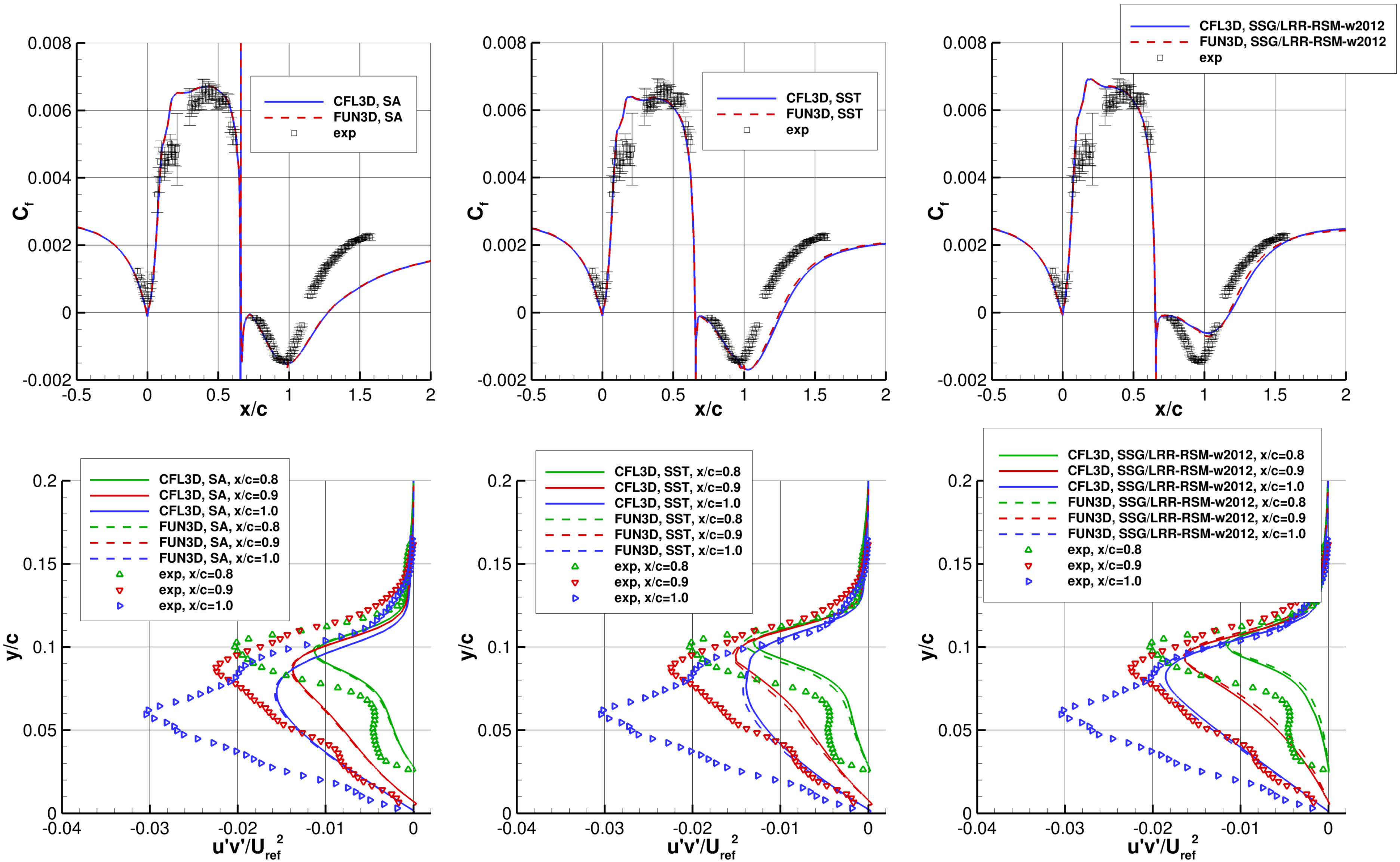






Case from CFDVAL2004 workshop
(no flow control)

2DWMH Validation Case

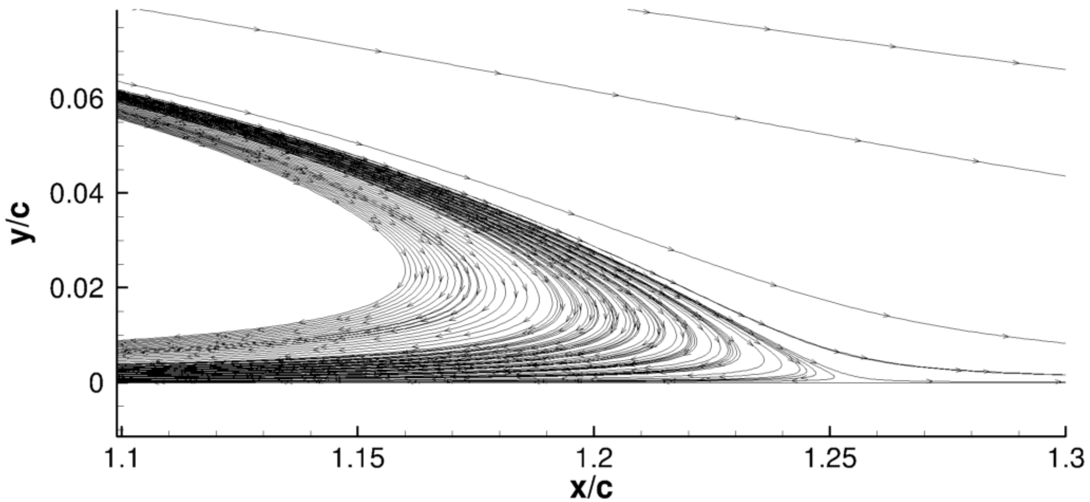


2DWMH Validation Case

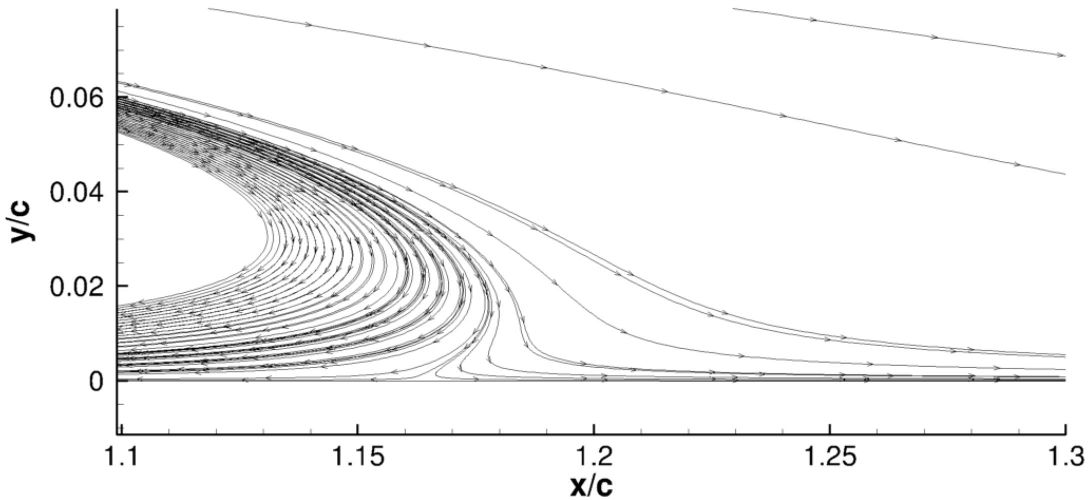
Quantity	exp	SA	SST	SSG/LRR-RSM
$(x/c)_{sep}$	0.66	0.66	0.65	0.65
$(x/c)_{reattach}$	1.10	1.28	1.26	1.18
$-[(u'v')/U^2]_{min,\ x/c=0.8}$	0.020	0.011	0.013	0.012
Error in bubble length		43%	40%	22%
Error in peak abs(u'v')		-45%	-35%	-40%

2DWMH Validation Case

SST



SSG/
LRR-
RSM



Other Aspects of TMR

- Databases
- Manufactured Solutions
- Numerical Analysis – recently added

Turbulent Flow Validation Databases

The data in the following links are publicly available and are provided here as a convenience. They are provided as-is and accuracy is not guaranteed; questions should be directed to the sources of the data provided.

- Data from "Collaborative Testing of Turbulence Models"
- Data from Other Experiments
- Data from Other Direct Numerical Simulations (DNS)
- Data from Other Large Eddy Simulations (LES)

Turbulent Manufactured Solutions

- Information from Lisbon "Workshop on CFD Uncertainty Analysis" series

Cases and Grids for Turbulence Model Numerical Analysis

- 2D Finite Flat Plate
- 2D NACA 0012 Airfoil
- 2D Hemisphere Cylinder <- under construction
- 3D Hemisphere Cylinder <- under construction

Data from "Collaborative Testing"

- From Bradshaw et al. (used with permission)
- Includes data from "Stanford Olympics"

Incompressible Flow Cases from 1980-81 Data Library

This grouping contains the incompressible-flow cases from the 1980-81 Data Library. The data in the original files are in normalized format, as explained on p. 60 of the 1980-81 Proceedings ("The 1980-81 AFOSR-HTTM Stanford Conference on Complex Turbulent Flows: A Comparison of Computation and Experiment," Volumes I, II, and III, edited by S. J. Kline, B. J. Cantwell, and G. M. Lilley, Stanford University, 1981). The 1980-81 Conference Proceedings also give a full description of the cases. (These cases comprise the contents of the original disk "d1", with the exception of 0411 (Cantwell cylinder), 0441 (Wadcock airfoil), 0511 (Shabaka wing-body junction), 0512 (Humphrey bend), which were too large to fit on the original disk.)

- Case F-0111: Developing Flow in a Square Duct (Po et al)
- Case F-0112: Secondary Currents in the Turbulent Flow Through a Straight Conduit (Hinze)
- Case F-0141: Increasingly Adverse Pressure Gradient Flow (Samuel and Joubert)
- Case F-0142: Six-Degree Conical Diffuser Flow, Low and High Core Turbulence (Pozzorini)
- Case F-0211: Effect of Free Stream Turbulence (Bradshaw and Hancock)
- Case F-0231: Turbulent Boundary Layers on Surfaces of Mild Longitudinal Curvature (Hoffmann and Bradshaw)
- Case F-0233: Turbulent Boundary Layer on a Convex, Curved Surface (Gillis and Johnston)
- Case F-0234: Effects of Small Streamline Curvature on Turbulent Duct Flow (Hunt and Joubert)
- Case F-0235: The Effects of Short Regions of High Surface Curvature on Turbulent Boundary Layers (Convex 30 degrees) (Smits et al)
  - Corrected data for Case F-0235
- Case F-0241: Zero Pressure Gradient Constant Injection (Andersen et al)
- Case F-0242: Adverse Pressure Gradient with Constant Suction (Andersen et al)
- Case F-0244: Zero Pressure Gradient with Constant Suction (Favre et al)
- Case F-0251: NLR Infinite Swept Wing Experiment
- Case F-0252: Part-Rotating Cylinder Experiment (Bissonnette et al)
- Case F-0253: Cylinder on a Flat Test Plate (Dechow and Felsch)
- Case F-0254: Part-Rotating Cylinder (Lohmann)
- Case F-0261: Turbulent Wall Jet Data Collected from Various Sources
- Case F-0311: Planar Mixing Layer Developing from Turbulent Wall Boundary Layers
- Case F-0331: The Turbulence Structure of a Highly Curved Mixing Layer (Castro)

etc…

Data from Other Experiments

- Experimental data posted (or linked) here
  - For data that may be useful for RANS development or validation

Experimental Data

- Common Research Model (independent website, will open new window)
- Shock Wave / Turbulent Boundary Layer Flows at High Mach Numbers (independent website, will open new window)
- 2-D Coanda Airfoil with Tangential Wall Jet (under construction)
- Round Synthetic Jets for Separation Control on 2-D Ramp
- FAITH Hill 3-D Separated Flow
- Flow Behind a NACA 0012 Wingtip
- Shock Boundary Layer Interaction at M=2.05 (under construction)

Data from Other DNS

- DNS data posted (or linked) here
  - For data that may be useful for RANS development or validation

Incompressible Flow Cases

- Channel Flow of Jimenez et al (independent website, will open new window)
- Boundary Layer Flow of Jimenez et al (independent website, will open new window)
- 3-D "Cherry" Diffuser (independent website, will open new window)
- Converging-Diverging Channel
- High-Order Moments in Unstrained and Strained Channel Flow

Compressible Flow Cases

- Compressible Supersonic Isothermal-Wall Channel Flow

Data from Other LES

- LES data posted (or linked) here
  - For data that may be useful for RANS development or validation

Incompressible Flow Cases

- Coanda Airfoil with Tangential Wall Jet
- Periodic Hill
- Curved Backward-Facing Step
- NASA Wall-Mounted Hump

Compressible Flow Cases

- None

Turbulent Manufactured Solutions

- From Eça (used with permission)
- Used for series of V&V workshops at IST (Lisbon)

Information from Lisbon "Workshop on CFD Uncertainty Analysis" series

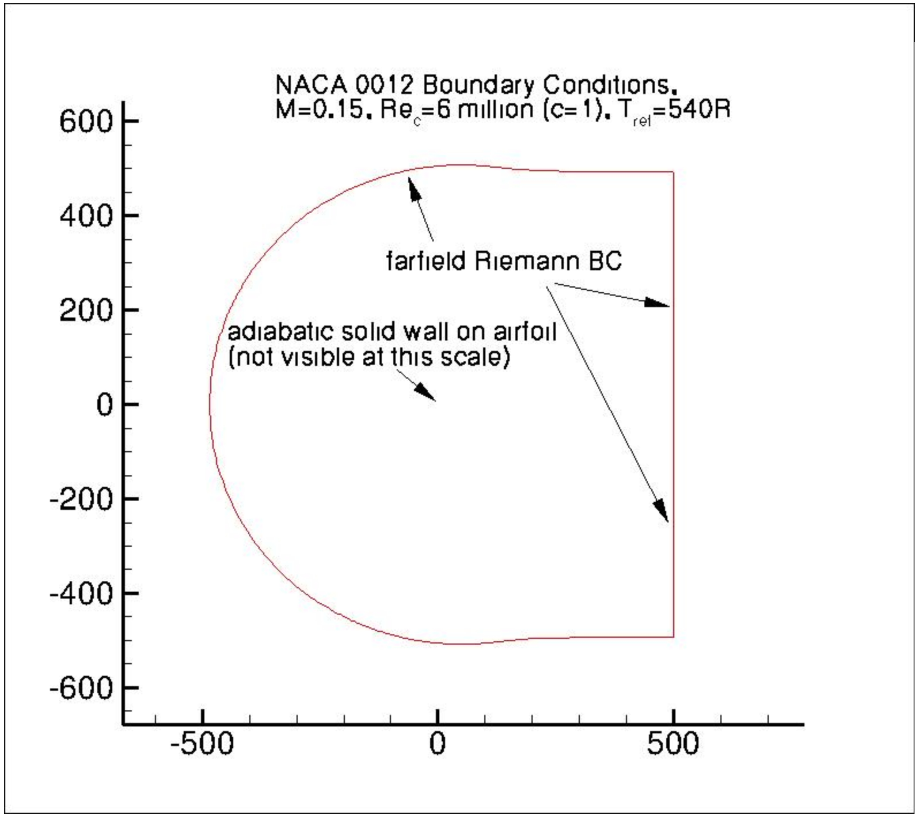
This web page provides some information from a series of turbulence-related Validation and Verification workshops held in Lisbon, Portugal, at the Instituto Superior Tecnico (IST). It includes manufactured solutions for wall-bounded incompressible turbulent flow. Everything on this page was provided courtesy of the workshop organizer Luis Eca, of IST. NASA assumes no responsibility for the accuracy of this information; questions should be directed to the originator. Additional details about the three workshops can be found in the American Institute of Aeronautics and Astronautics papers AIAA-2005-4728 (Toronto, June 2005), AIAA-2007-4089 (Miami, June 2007), and AIAA-2009-3647 (San Antonio, June 2009). See also Int. J. Numer. Meth. Fluids 54:119-154, 2007 and Int. J. Computational Fluid Dynamics 21(3-4):175-188, 2007 for details on the construction of manufactured solutions for one- and two-equation eddy-viscosity turbulence models.

- **Note describing test cases for the third workshop** (pdf file)
- **Note describing validation procedure for the third workshop** (pdf file)
- **Report IST D72-34 (2005), describing turbulent manufactured solutions for the workshop** (pdf file)
- **Report IST D72-36 (2006), describing turbulent manufactured solutions for the workshop** (pdf file)
- **Note describing manufactured functions available** (pdf file)
- **Fortran files associated with the workshop** (tarred and gzipped directory)

Turbulence Model Numerical Analysis

- Purpose: more in-depth analysis of particular cases
- Different / finer grids than those on validation pages
- Pages still under development
  - Coordinated with FDTC Solver Technology for Turbulent Flows DG
  - Currently focused on SA model only
- See, e.g., Diskin et al.: AIAA-2015-1746

Numerical Analysis – NACA 0012



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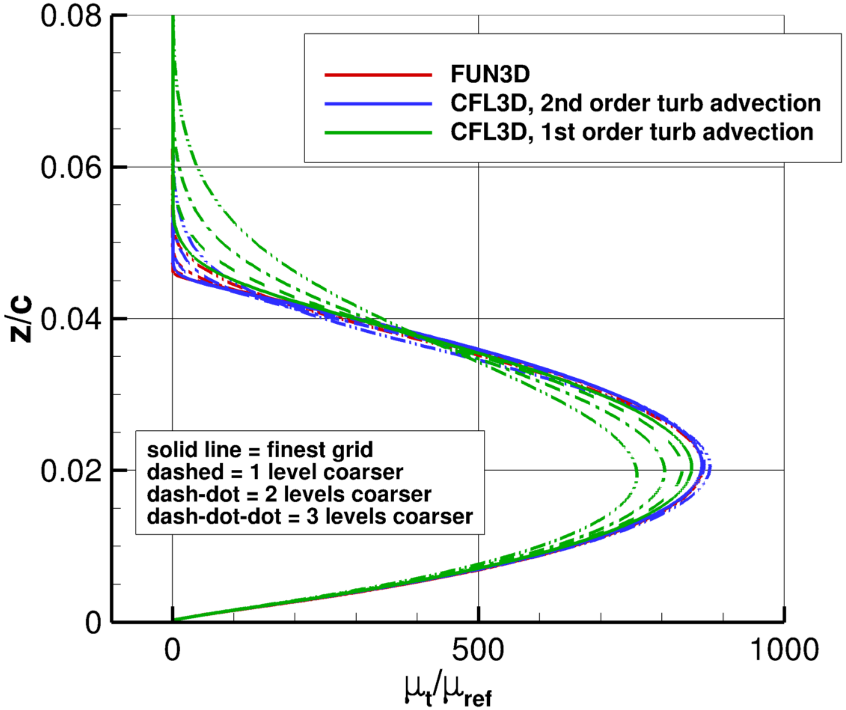


- Based on grid convergence study results (using over 14 million grid points) and 3 codes (plus others in AIAA special session SciTech 2015), we have a good sense of the "reference solution", even without clear asymptotic rates of convergence
    - E.g., CL to within 0.0002, or 0.02%
    - E.g., CD to within 0.00001, or 1/10th drag count

Includes additional analysis of streamwise grid resolution influence near T.E.

Summary

- TMR seeks to bring consistency to the testing, verification, and validation of RANS turbulence models for the CFD community
- One of biggest reason for its success may be its "openness"
  - By including all details (equations, grids, BCs, existing CFD results), it encourages quick comparisons and makes inter-organizational collaborations easier
  - Mistakes on the website are occasionally found by the community; its openness makes the process of finding and fixing them more efficient
  - TMBWG is an open working group; anyone can join

Future Plans

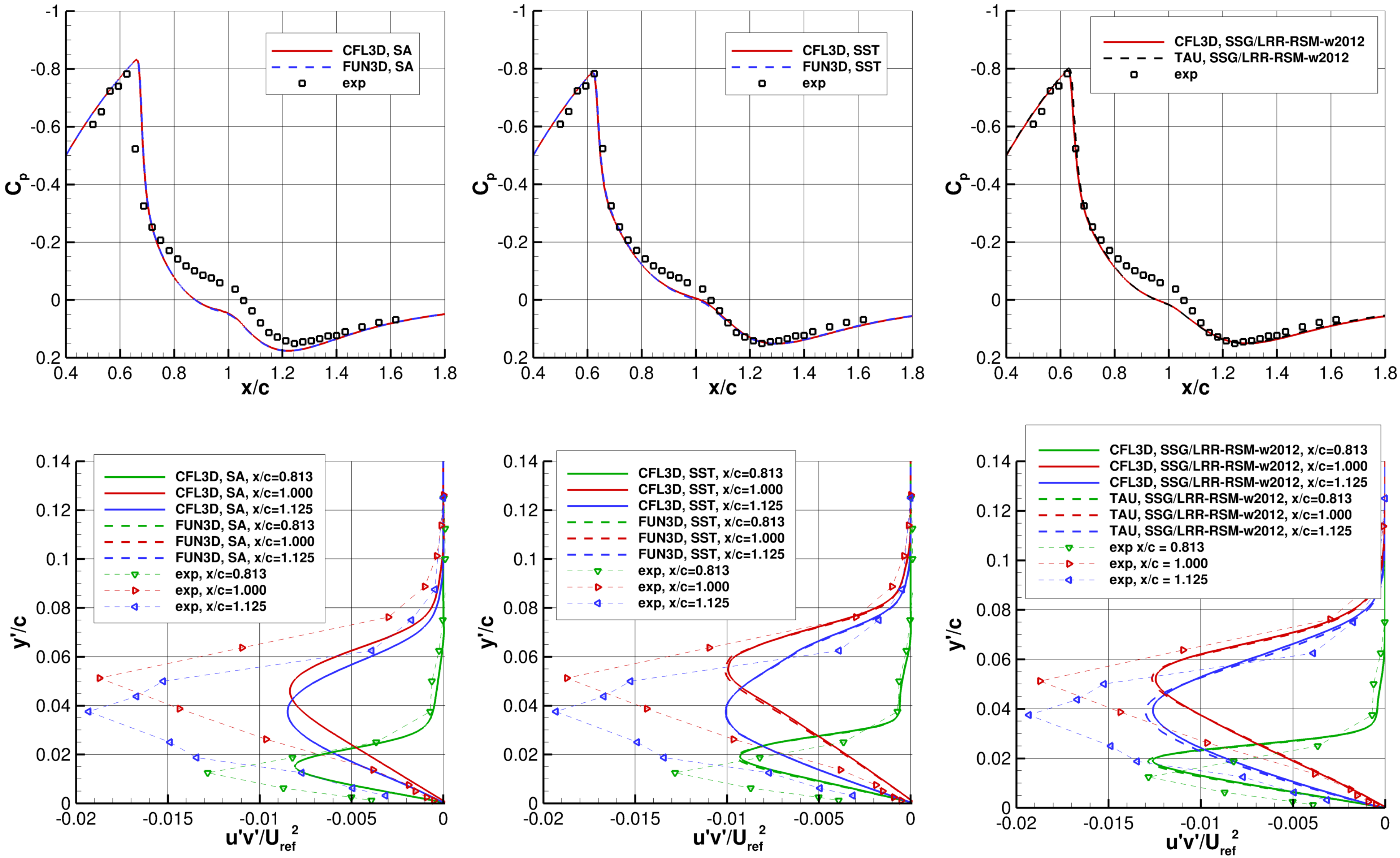
- Continue to add relevant validation cases, with help from the TMBWG
- Continue to add descriptions of new models as appropriate
- Continue to add helpful databases as available
- Verify and validate additional models on the existing test cases
  - This is the most time-consuming task (15+ cases, grid convergence studies, 12 turbulence models *and variants*, and desire for at least two independent codes to "agree")
  - SA, SST, SST-V, Wilcox2006, and SSG/LRR-RSM-w2012 have had most of the focus to this point

Open Questions

- How to find the time to verify/validate additional models for posting to TMR?
  - Most efforts to date have involved author's collaboration
- How to create stronger connection between the TMR and researchers with new RANS ideas?
  - Original hope for site: to facilitate the dissemination of new turbulence models to the community
  - To date, very few modelers have done this
- How to handle the fact that codes (and their results) might change over time?
- Are transition models appropriate for the TMR?
- What about hybrid RANS-LES models?
  - They can be described, but how to verify them?

Backup slides

ATB Case



CFL3D, SA
FUN3D, SA
exp
CFL3D, SST
FUN3D, SST
CFL3D, SSG/LRR-RSM-w2012
TAU, SSG/LRR-RSM-w2012
C_p
x/c
CFL3D, SA, x/c=0.813
CFL3D, SA, x/c=1.000
CFL3D, SA, x/c=1.125
FUN3D, SA, x/c=0.813
FUN3D, SA, x/c=1.000
FUN3D, SA, x/c=1.125
exp, x/c=0.813
exp, x/c=1.000
exp, x/c=1.125
CFL3D, SST, x/c=0.813
CFL3D, SST, x/c=1.000
CFL3D, SST, x/c=1.125
FUN3D, SST, x/c=0.813
FUN3D, SST, x/c=1.000
FUN3D, SST, x/c=1.125
CFL3D, SSG/LRR-RSM-w2012, x/c=0.813
CFL3D, SSG/LRR-RSM-w2012, x/c=1.000
CFL3D, SSG/LRR-RSM-w2012, x/c=1.125
TAU, SSG/LRR-RSM-w2012, x/c=0.813
TAU, SSG/LRR-RSM-w2012, x/c=1.000
TAU, SSG/LRR-RSM-w2012, x/c=1.125
exp x/c = 0.813
exp, x/c = 1.000
exp, x/c = 1.125
y'/c
$u'v'/U_{ref}^2$

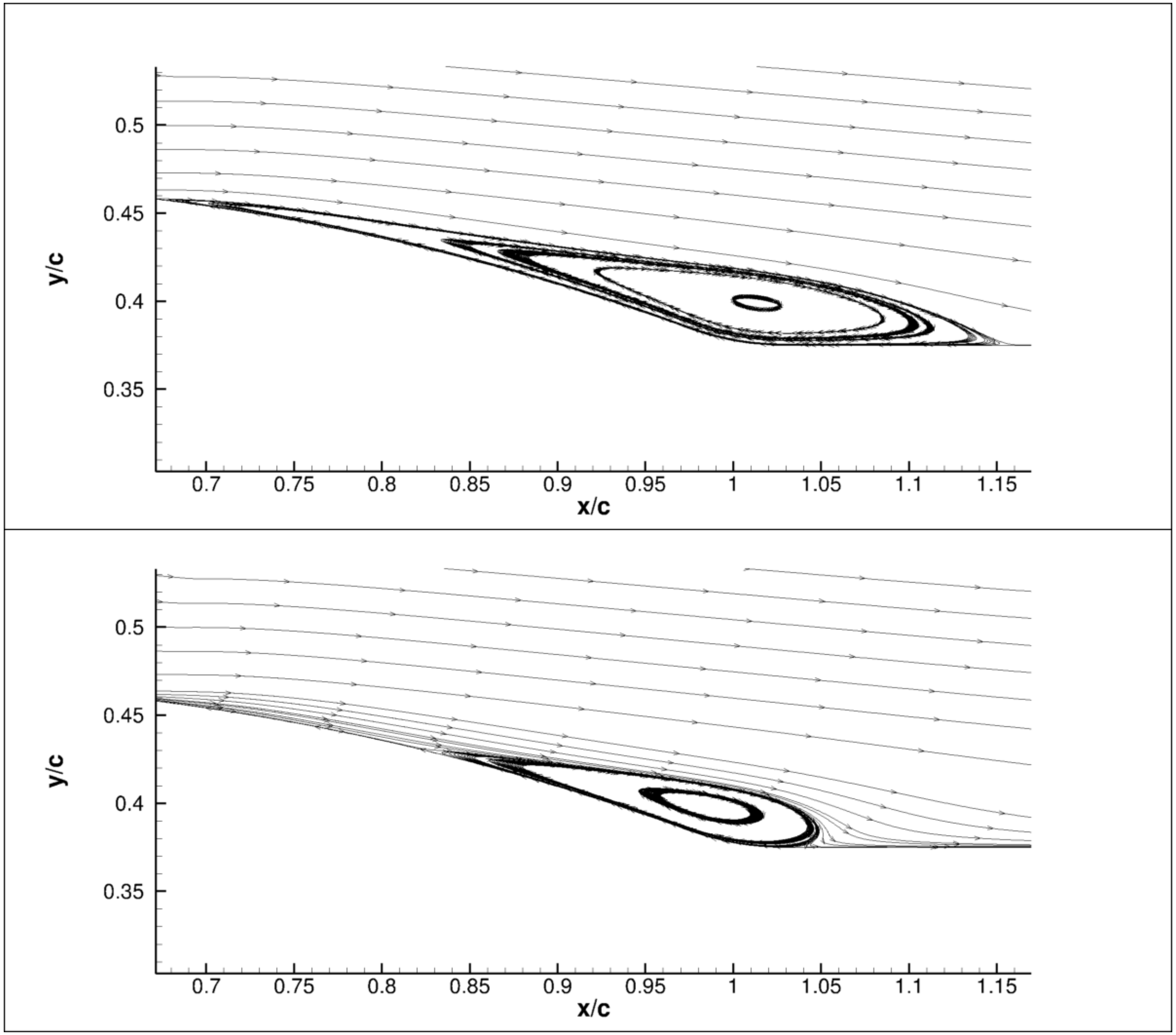
ATB Case

Quantity	exp	SA	SST	SSG/LRR-RSM
$(x/c)_{sep}$	0.70	0.69	0.65	0.66
$(x/c)_{reattach}$	1.10	1.16	1.16	1.05
$-[(u'v')/U^2]_{min,\ x/c=0.8}$	0.019	0.008	0.010	0.013
Error in bubble length		18%	28%	-3%
Error in peak abs(u'v')		-58%	-47%	-32%

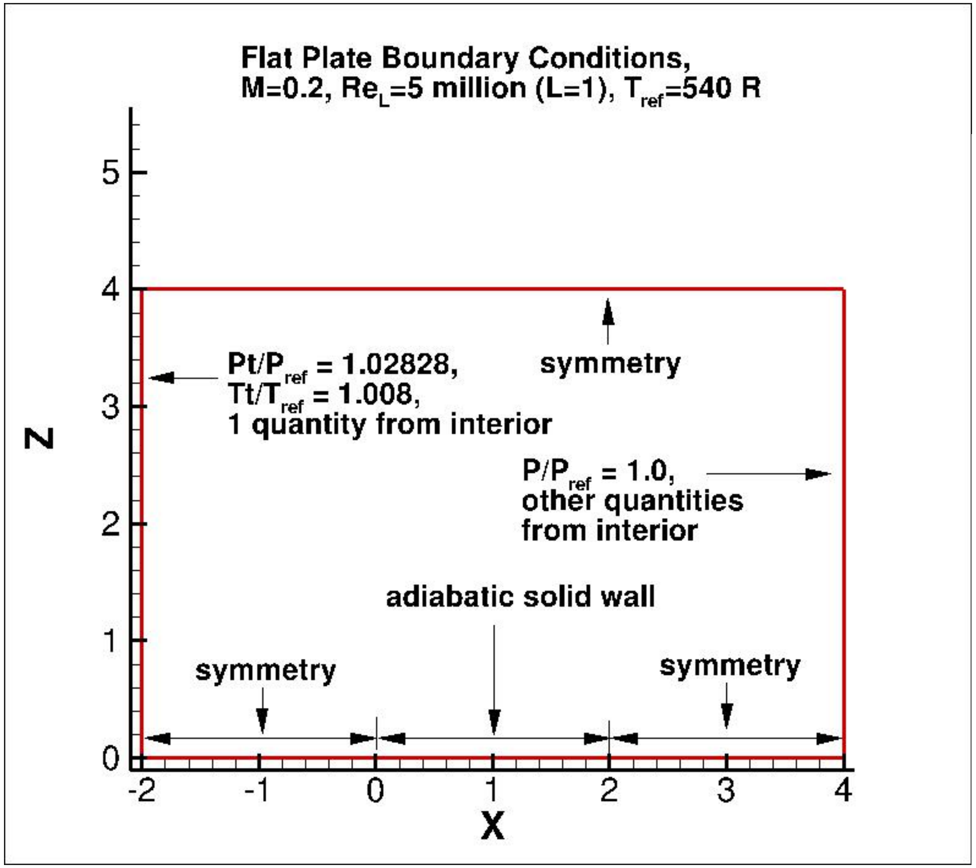
ATB Case

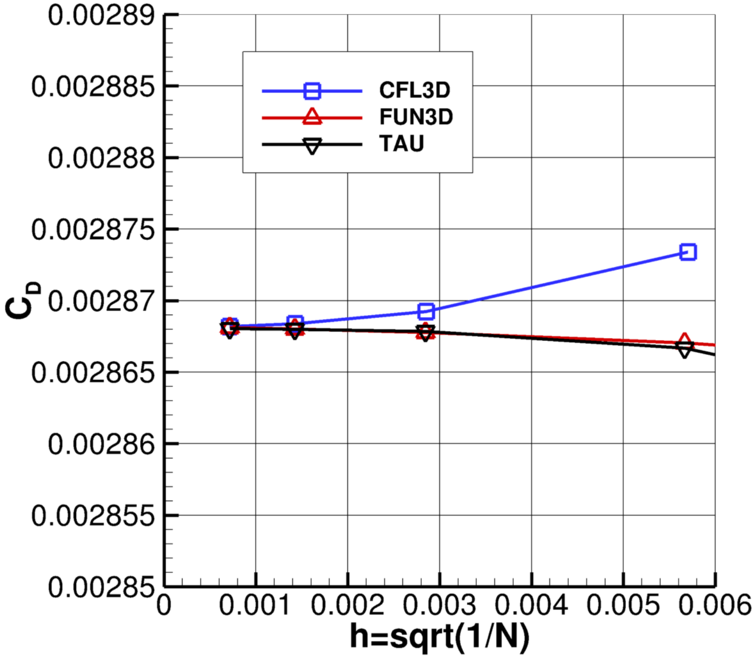
SST

SSG/
LRR-
RSM



Numerical Analysis – Finite Flat Plate





- Different from verification & validation cases because wake added behind plate
- New finer grids (up to 2561x769) with aspect ratios approx 1 near L.E. and T.E.