VERIFICATION AND VALIDATION OF THE CAELUS LIBRARY - INCOMPRESSIBLE TURBULENCE MODELS

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- Is a derivative of OpenFOAM® .
- Open Source (GPL): www.caelus-cml.com.
- Supports multiple platforms (Windows, Linux and Mac).
- Easy to install and compile.
- Improved algorithmic robustness on non-"perfect" meshes.
- Improved accuracy on non-"perfect" meshes.
- Stable, predictable API.
- Documentation and validation cases.
- Verified schemes and **Validated solvers and turbulence models.**

Motivation

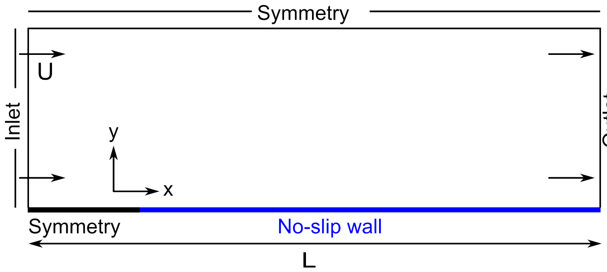
- Very few open source CFD solvers and libraies perform or publish verification and validation studies.
- No comprehensive published verification and validation of the turbulence models in OpenFOAM® .
- This work validates a select number of the RANS turbulence models implemented in Caelus.
  - Turbulence models used include k-ω SST, Spalart-Allmaras, and realizable k-ϵ models.
- Verification and validation of these turbulence models was conducted using openly available experimental, theoretical, and numerical data.

Results

- Presented test cases obtained from the NASA Langley Turbulence Modeling Resource website `http://turbmodels.larc.nasa.gov`.
- Caelus simulations are incompressible, but comparison results are from compressible solvers.
- Steady-state solver using Caelus version 6.10.
- Pressure-velocity coupling was achieved via a predictor-corrector algorithm.
- 2^{nd} order finite volume method.
- Advection terms - linear upwind with Barth-Jespersen limiter.
- Upwind used for advection of turbulent quantities.

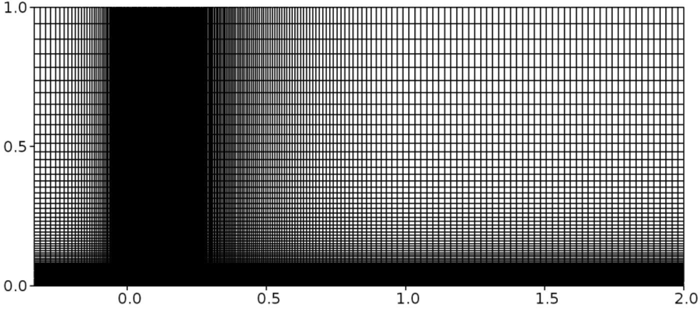
Zero Pressure Gradient Flat Plate

- Zero pressure gradient flow over 2D flat plate with sharp-leading edge.
- Grid convergence study carried out with 4 grids and solutions compared with CFL3D data.
- Plate skin-friction coefficient c_f was used to verify the accuracy of the results.
- Freestream velocity of $69.436\ ms^{-1}$ and Re = 5×10^6.



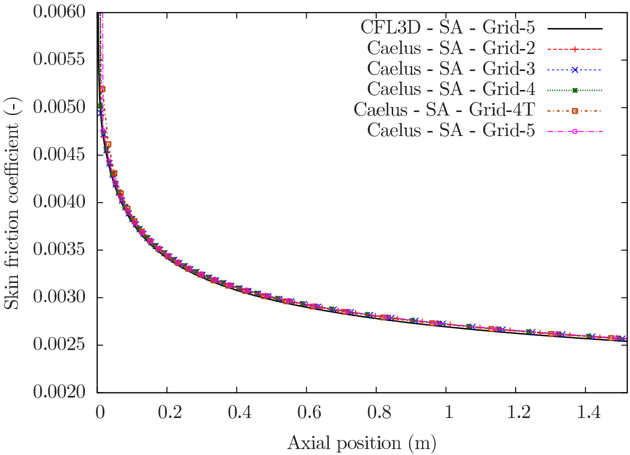
Zero Pressure Gradient Flat Plate cont'd

Grid #	points x-dir	points z-dir	Total	y^+
2	68	48	3264	0.405
3	136	96	13,056	0.203
4	272	192	52,224	0.101
4T	triangular	prisms	104,448	0.059
5	544	384	208,896	0.05



Zero Pressure Gradient Flat Plate cont'd

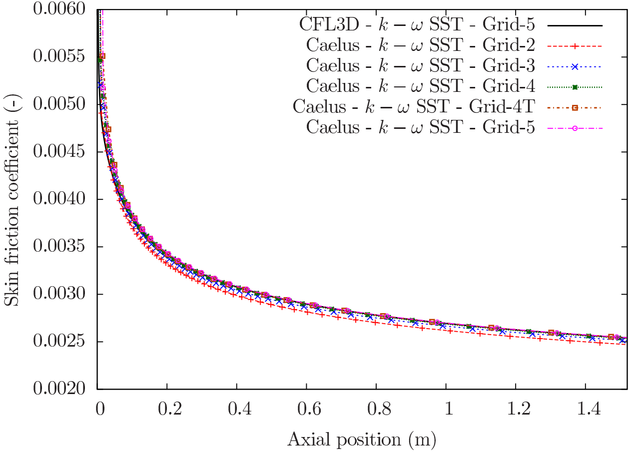
- Skin friction from Spalart-Allmaras model



- Caelus results are in close agreement with CFL3D.

Zero Pressure Gradient Flat Plate cont'd

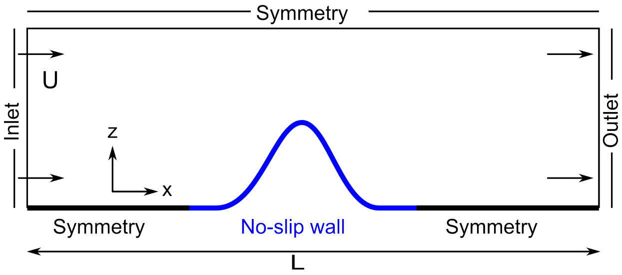
- Skin friction from k-ω SST model



- Caelus results are in close agreement with CFL3D.

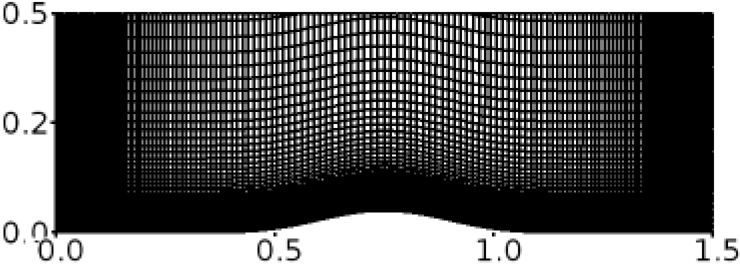
2D Bump in Channel

- Flow over a 2D bump in a channel.
- Grid convergence study carried out for 4 grids and 2 turbulence models.
- Solutions compared with CFL3D data.
- Skin-friction coefficient c_f was used to verify the accuracy of the results.
- Freestream velocity of $69.436\ ms^{-1}$ and Re = 3×10^6.



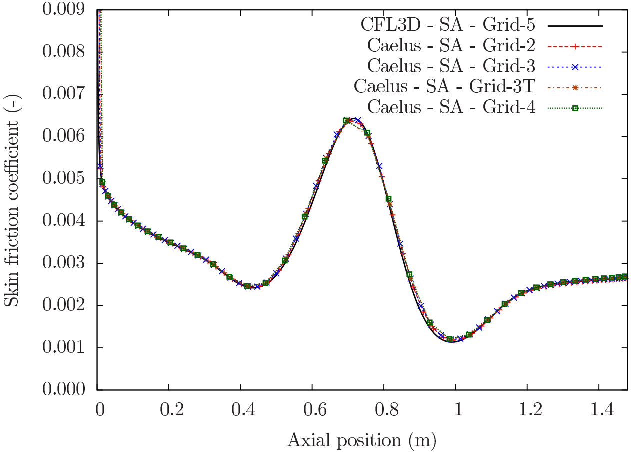
2D Bump in Channel cont'd

Grid #	points x-dir	points z-dir	Total	y^+
2	176	80	14,080	0.236
3	352	160	56,320	0.118
3T	Triangular	prisms	112,640	0.07
4	704	320	225,280	0.059



2D Bump in Channel cont'd

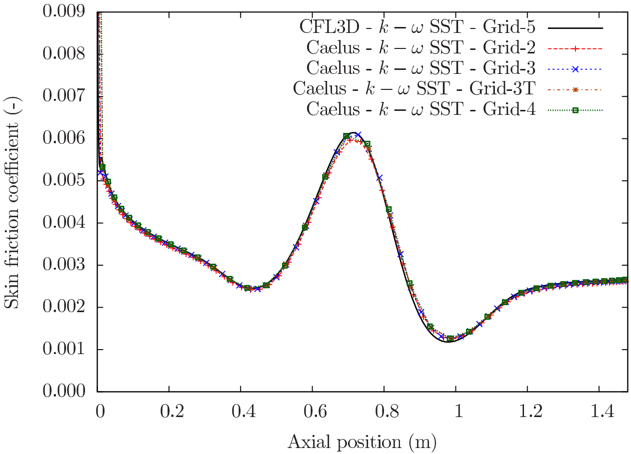
- Skin friction from Spalart-Allmaras model



- Caelus results are in close agreement with CFL3D.

2D Bump in Channel cont'd

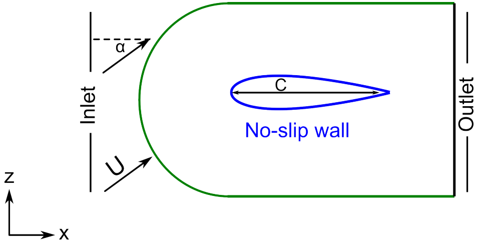
- Skin friction from k-ω SST model



- Caelus results are in close agreement with CFL3D.

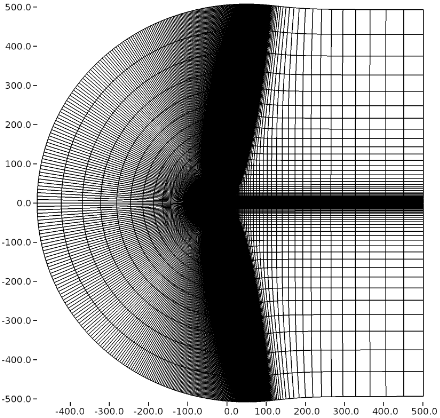
2D NACA 0012 Airfoil

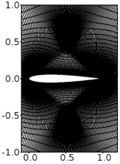
- Flow over a 2D NACA 0012 airfoil. Two angles of attack were considered: $\alpha = 0^\circ$ and 10°.
- Grid convergence study carried out with 3 grids and solutions compared with CFL3D and experimental data.
- Skin-friction c_f and pressure coefficient c_p were used to verify the accuracy of the results.
- Freestream velocity of $52.077\ ms^{-1}$ and Re = 6×10^6.



2D NACA 0012 Airfoil cont'd

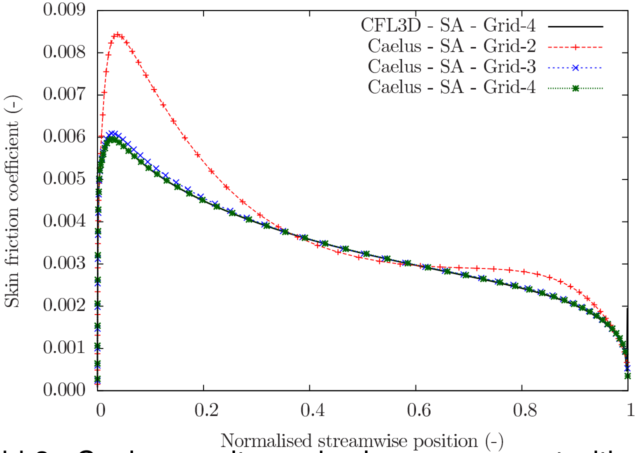
Grid #	points x-dir	points z-dir	Total	y^+
2	128	64	14,336	0.465
3	256	128	57,344	0.209
4	512	256	229,376	0.098





2D NACA 0012 Airfoil cont'd

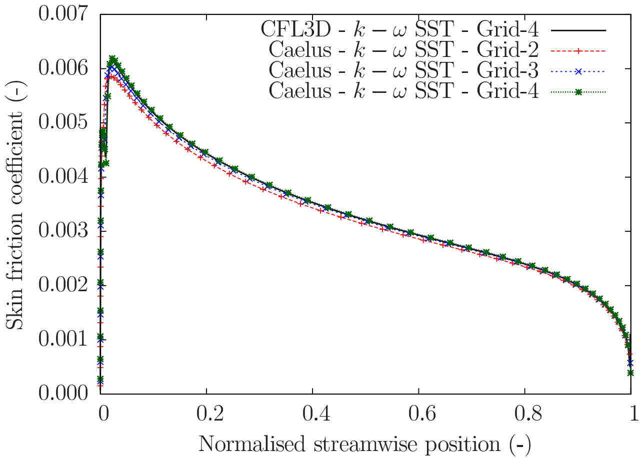
- Skin friction from Spalart-Allmaras model ($\alpha = 0°$)



- Grid-3+ Caelus results are in close agreement with CFL3D.

2D NACA 0012 Airfoil cont'd

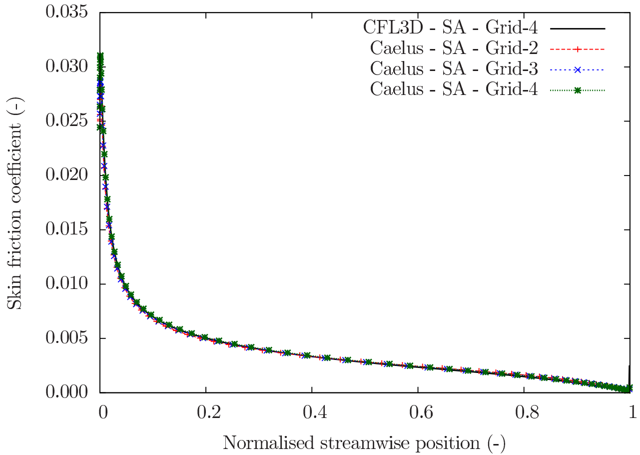
- Skin friction from k-ω SST model ($\alpha = 0°$)



- Caelus results are in close agreement with CFL3D.

2D NACA 0012 Airfoil cont'd

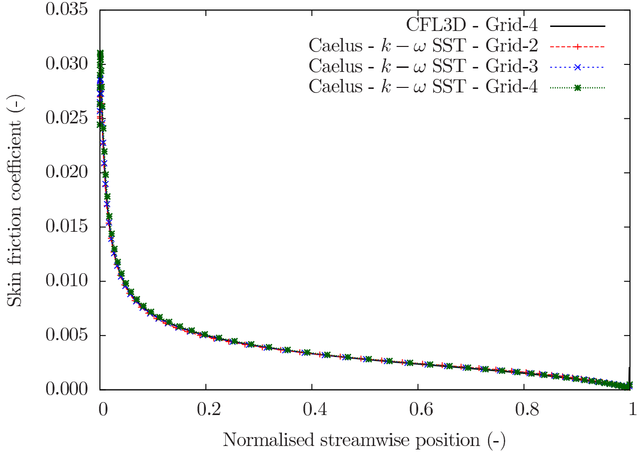
- Skin friction from Spalart-Allmaras model ($\alpha = 10°$)



- Caelus results match CFL3D.

2D NACA 0012 Airfoil cont'd

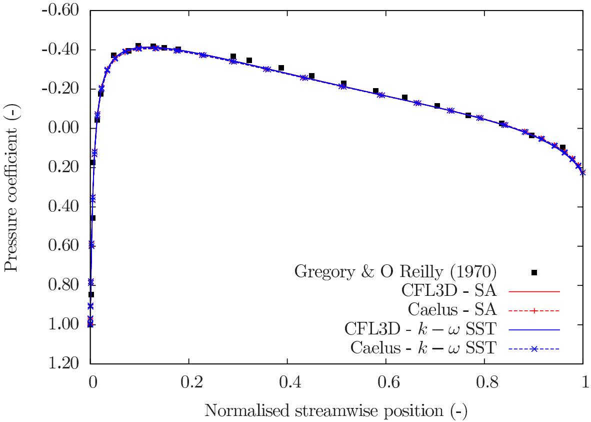
- Skin friction from k-ω SST model ($\alpha = 10°$)



- Caelus results match CFL3D.

2D NACA 0012 Airfoil cont'd

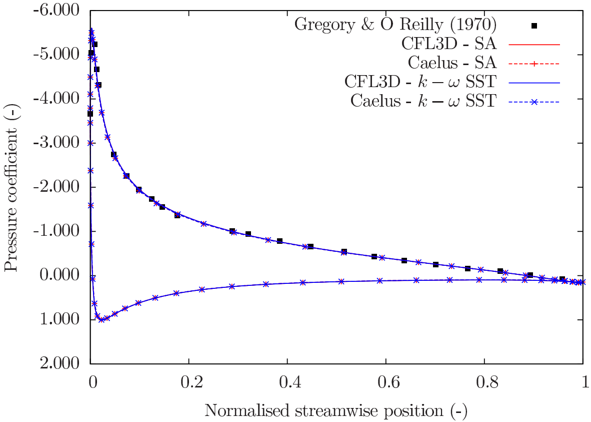
- Pressure coefficient from Spalart-Allmaras and k-ω SST models ($\alpha = 0°$)



- Caelus results match CFL3D and experiment.

2D NACA 0012 Airfoil cont'd

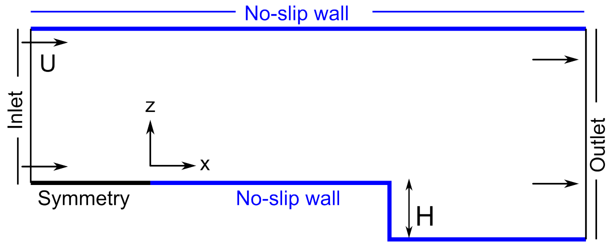
- Pressure coefficient from Spalart-Allmaras and k-ω SST models ($\alpha = 10°$)



- Caelus results match CFL3D and experiment.

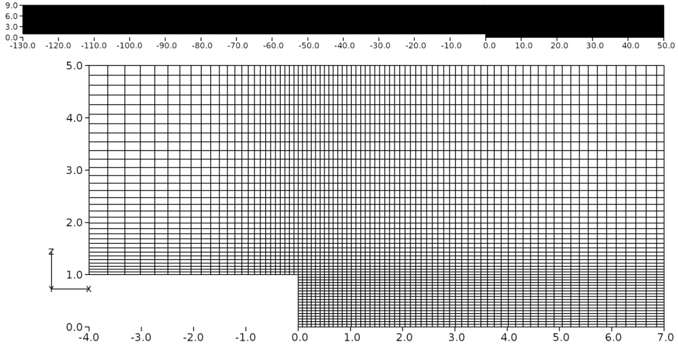
Backward Facing Step

- Flow over a 2D backward facing step.
- Efficacy of wall functions for separated flow is evaluated.
- Turbulence models Spalart-Allmaras, k-ω SST and realizable k-ϵ compared with CFL3D and experimental data
- Skin-friction c_f and pressure c_p coefficient were used to verify the accuracy of the results.
- Freestream velocity of $44.315\ ms^{-1}$ and Re = $36,000$.



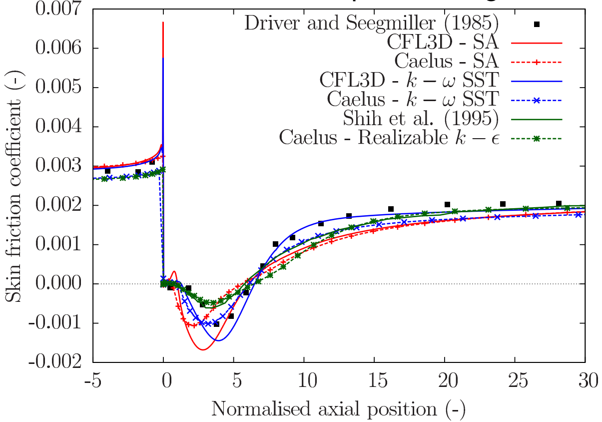
Backward Facing Step cont'd

- 14,676 elements, $y^+ \sim 30$.
- CFL3D results obained on a $y^+ \sim 1$ grid.



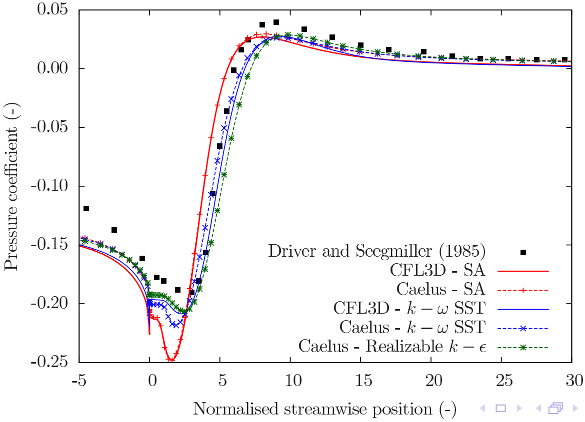
Backward Facing Step cont'd

- Upstream of the step, agreement is quite good.
- Downstream, post-reattachment under predicts c_f.
- k-ω SST turbulence model gives closest to the experimental data within the separated region.



Backward Facing Step cont'd

- c_p from k-ω SST and realizable k-ϵ are quite close over entire region and in fair agreement with experimental data.
- Spalart-Allmaras shows significant deviation in region of pressure minima.



Backward Facing Step cont'd

- A key feature when modelling the backward facing step is prediction of the reattachment location downstream of the step.
- Of the models considered, the realizable k-ϵ prediction is best agreement with the experimentally obtained value.

Type	Reattachment location (x/H)
Experimental	6.26 ± 0.10
SA	5.55
k-ω SST	6.08
k-ϵ	6.27

Summary

- Several verification and validation cases for a steady, turbulent, incompressible flow have been described.
- On selected cases grid independence was demonstrated.
- All results were compared to the previously verified and validated solver, CFL3D, and where available, experimental data.
- The incompressible RANS turbulence models implemented in Caelus faithfully represent the known performance of each model.

Applied CCM

- Specialise in the application, development and support of OpenFOAM® - based software
- Creators and maintainers of caelus
- Locations: Australia, Canada, USA