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Launch Vehicle Simulations using the Faster & Improved Density-Based Coupled Solver in iconCFD ® V5

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Agenda

- Introduction
- New Features
- Validation Results
- Industrial Case Studies
- Conclusions

Introduction

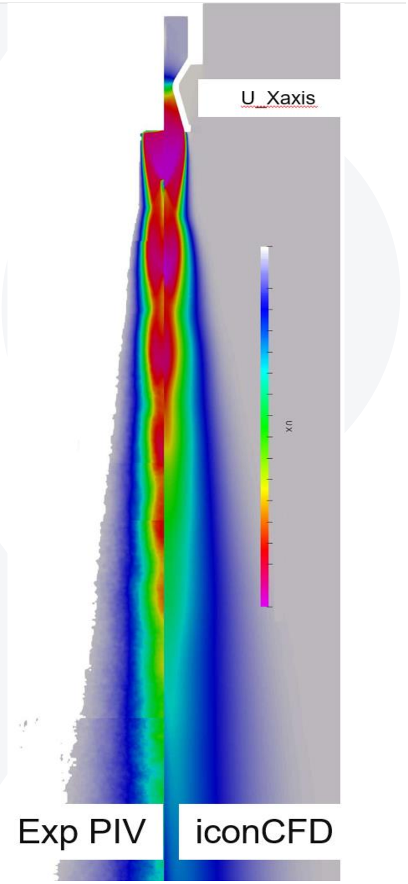
iconCFD HiSPAC

- **iconCFD HiSPAC** – *High Speed Accurate and Coupled* is the iconCFD module in V5 for high speed compressible aerodynamics (formerly known as iconCFD Transonic in V4)
- The density-based solver in the iconCFD V5 HiSPAC module is called **iconHiSPACSolve**
- The Navier-Stokes equations are solved as a fully coupled, implicit system, linearised in time
- The convective flux discretisation uses a 2^{nd} order flux limiting method combining a nominally 2^{nd} order central scheme with a 1^{st} order upwind Roe formulation
- A vanLeer flux limiter is applied using the Harten-Hyman entropy fix within the Roe method
- The diffusive flux discretisation uses a 2^{nd} order approximate central scheme with the gradients reconstructed to the face centres
- Approximate formulations of the viscous and convective Jacobians are used, with the TSL assumption applied to the gradient derivatives
- Both steady state and transient time integration is available, with steady-state obtained through a local time stepping scheme

Introduction

iconCFD HiSPAC

- The turbulence equations are treated in segregated manner, with the coupling performed through the mass flux , $\rho\vec{U}$, and the turbulent eddy viscosity, μ_T
- There is a large choice of RANS, DES and LES models
- The thermophysical models are based on a thermally perfect gas and use Sutherland's Law to calculate laminar eddy viscosity based on temperature
- Both calorically perfect and imperfect gases are supported and can be applied to both single- or multi-species simulations
- Boundary condition application is through a novel approach
  - Boundary types applied to patches rather than per-field approach
  - Multiple boundary types can be specified by the user, to obtain desired behaviour i.e. "Adiabatic" + "No-slip" + "Wall"
  - Solution vector boundary conditions handled internally in solver



Example of multispecies case, courtesy of CNES

New Features

Parallel Performance

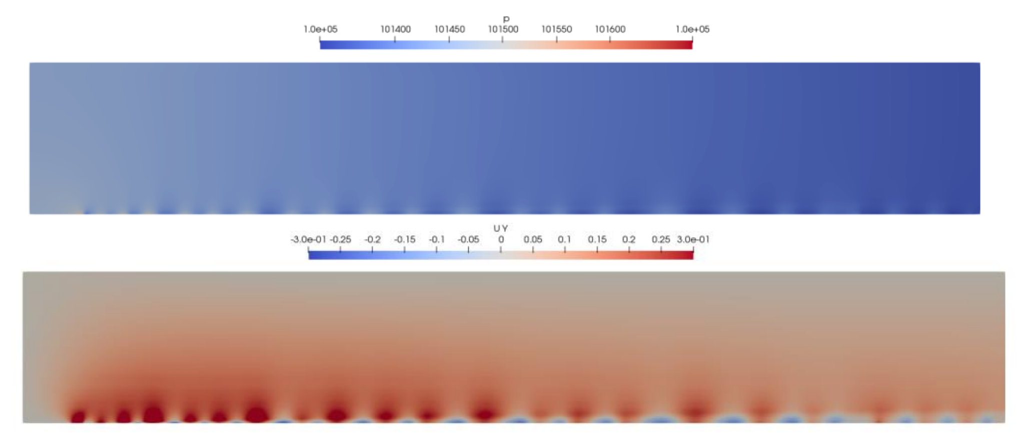
- Significant improvements in the parallel performance were made in the 4.2 release line
- This has delivered up to **~90% reduction** in time on some cases
- These improvements are available from iconCFD v4.2.11 onwards, and will evidently be available in iconCFD V5 as well

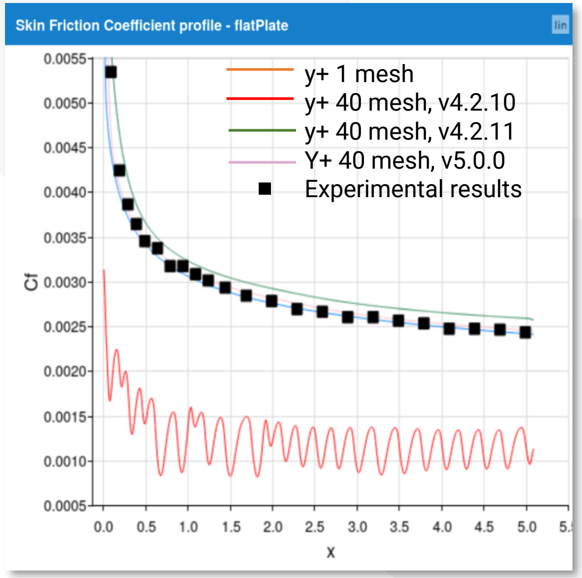
200 iterations	Final Time (s)		
nProcessors	**v4.2.8**	**v4.2.11**	**%Reduction**
40	628	582.32	**7.27**
160	1853	204.04	**88.99**

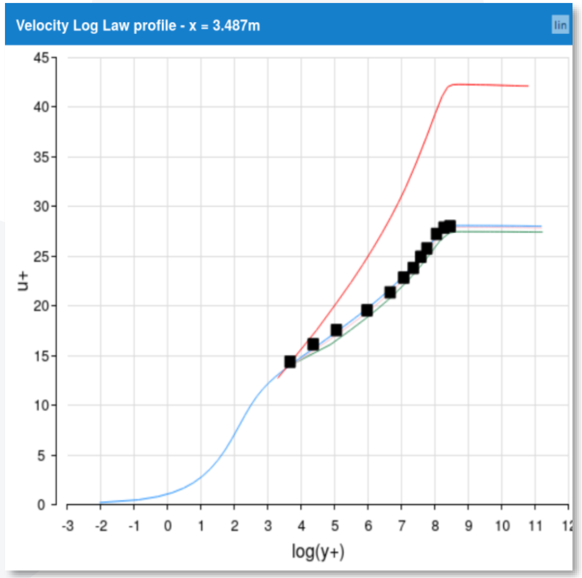
New Features

Wall Functions

- The solver was developed for boundary resolving meshes, however wall functions may be required for large industrial cases
- Industrial aerospace testcase with y+ $\mathcal{O}(100)$ showed pressure oscillations on surface
- Replicated on flat plate case with y+ = 40
  - Poor agreement with flat plate theory and experimental results
  - Oscillatory behaviour along plate surface
- Significant improvements were made to the wall function treatment in iconCFD V4 (v4.2.11) for adiabatic walls
- This was improved and extended to all wall behaviours in iconCFD V5







New Features

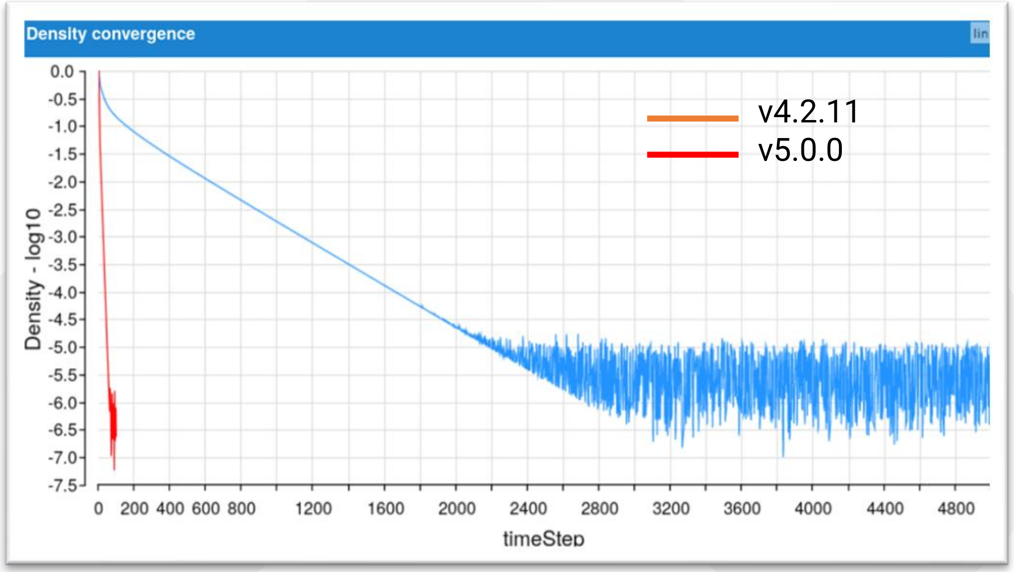
Boundary Condition Enhancements

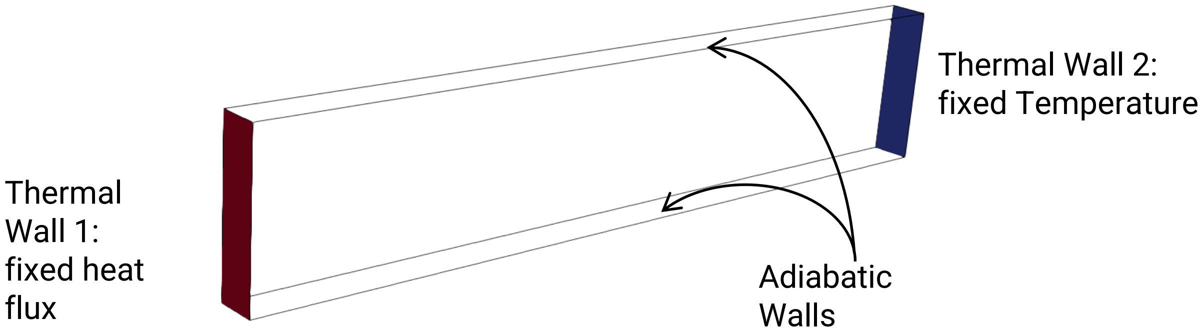
- In order to improve convergence of the solver, the boundary condition approach was reviewed
- Key areas for improvement were identified, including
  - Fully utilising the per-boundary approach to setting the physical conditions at the boundary
    - Direct specification of flux and jacobian at boundary – derived per boundary
  - Moving to a fully numerical scheme agnostic approach
  - Further development of the wall function support
- This is a new feature in iconCFD V5 which has proven to give faster convergence and improved stability of the solver

Validation Results

2D Turbulent Heated Box: Thermal Walls

- Development test case for thermal walls
- Analytical solution exists for validation
- iconCFD V5 shows a **97% reduction** in time to convergence
  - Reduced number of iterations
  - Small improvement in solution





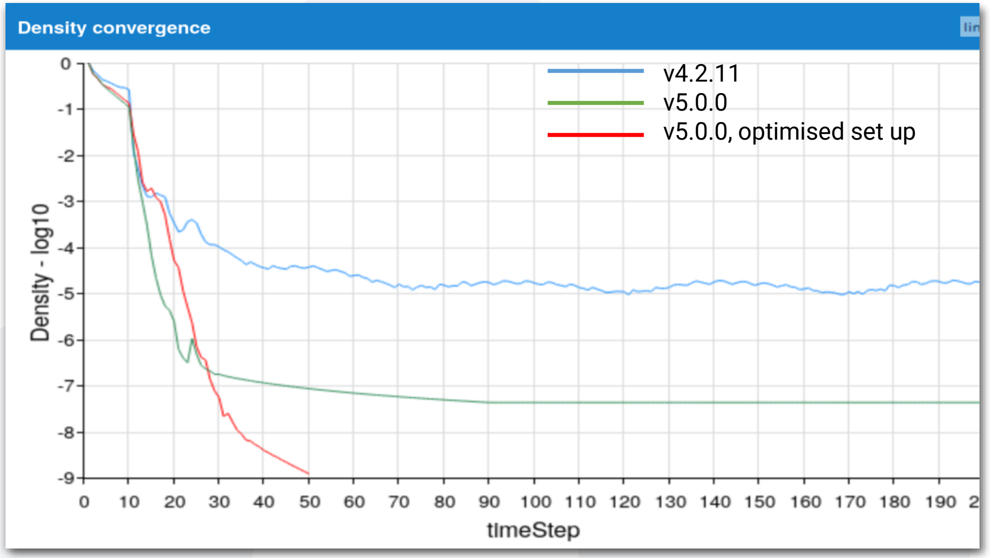
iconCFD version	Total clock time [s]	n iter	% Error in Temperature for Thermal wall 1 compared to analytical solution
v4.2.11	11.42	5000	0.00558
v5.0.0	0.38	100	0.00415

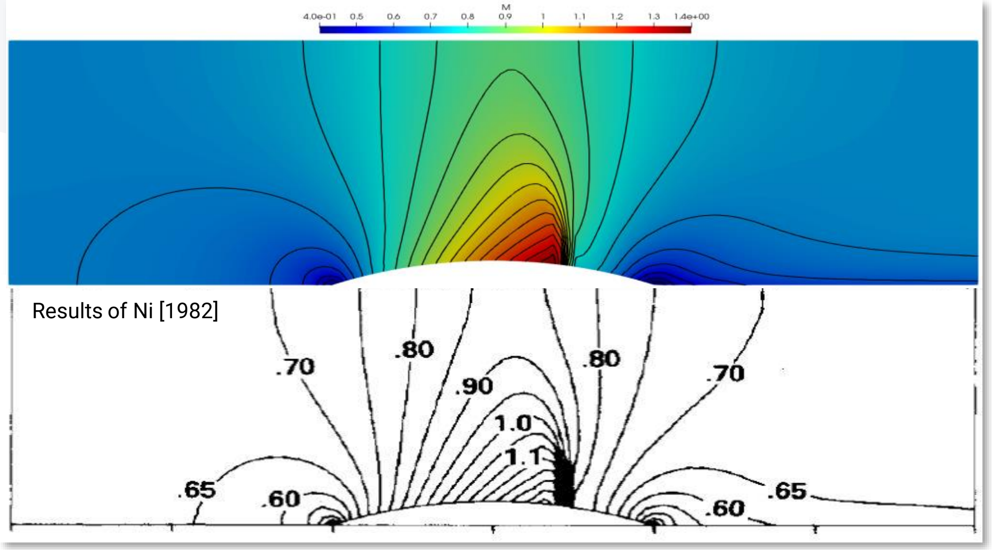
Validation Results

2D Euler Transonic Bump

- Development test case for shock formation
- Computational results available for verification
- **Significant improvement** in convergence with iconCFD V5 is observed
- Due to **improved stability**, further improvement was found by optimizing the case (i.e. increasing max CFL and ramp rate):
    - Reduction in number of iterations required
    - **4 orders of magnitude** drop in density residual compared to baseline
    - **~65% reduction** in time to convergence

iconCFD version	Total clock time [s]	n iter
v4.2.11	16.19	200
v5.0.0, optimised set up	5.7	50



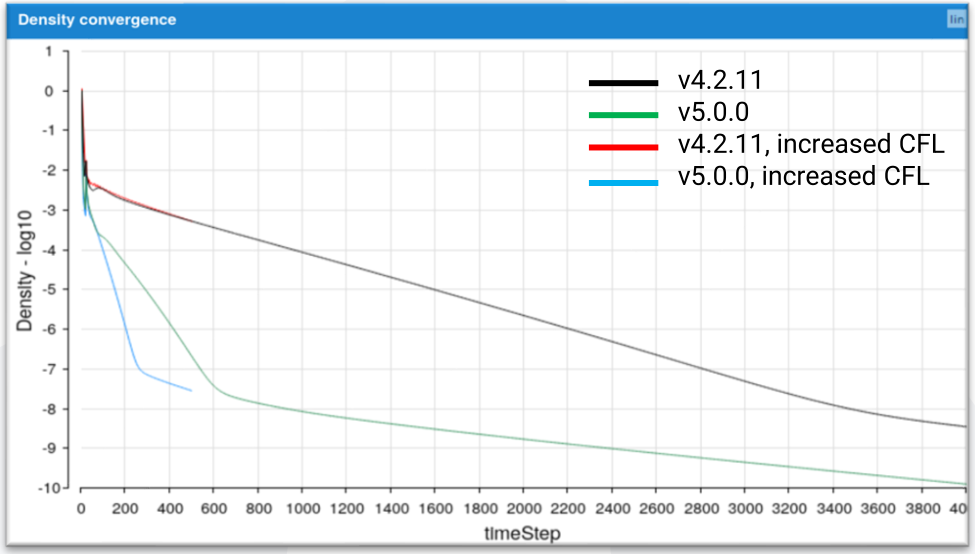


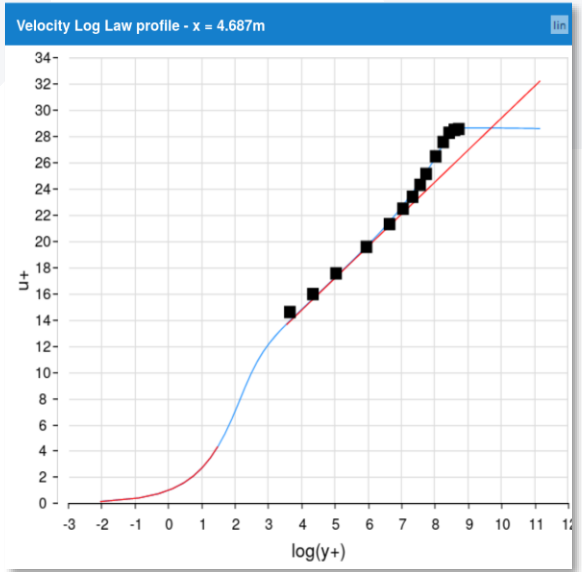
Validation Results

2D Turbulent Flat Plate

- Validation test for boundary layer formation
- y+ = 1 NPARC structured mesh
- **Significant improvement** in convergence with iconCFD V5 for same test set up
- Improvements found by **increasing CFL** (not observed for iconCFD V4 (v4.2.11))
  - Reduced number of iterations from 4000 to 500
  - **~83.5% reduction** in time to convergence

iconCFD version	Total clock time [s]	n iter	Ave. time per iter. [s]
v4.2.11	692	4000	0.1697
v5.0.0. optimised set up	114	500	0.2263

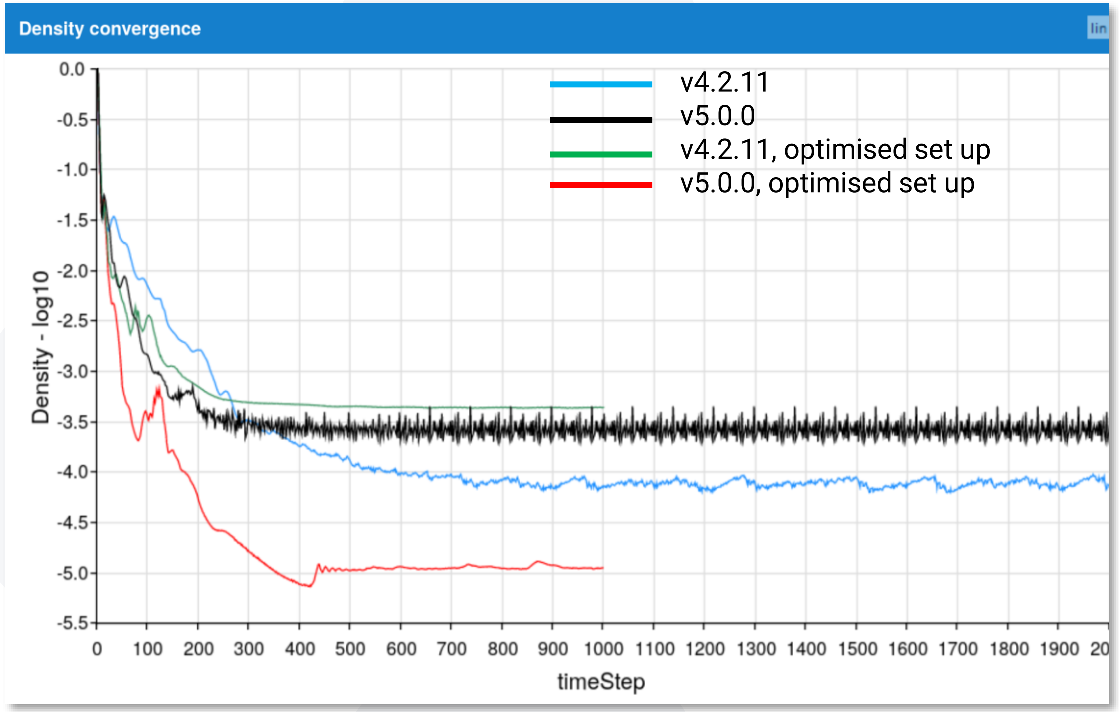


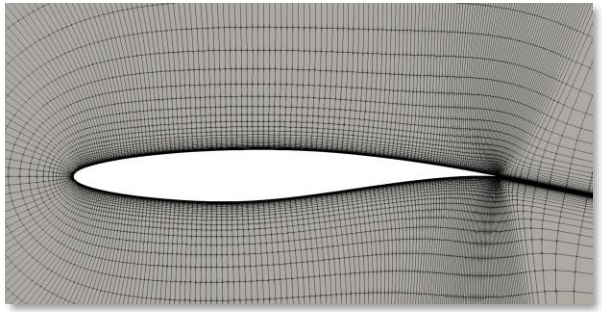


Validation Results

RAE2822: 2D Transonic Airfoil

- NPARC y+ 1 structured mesh
- M = 0.729, alpha = 2.31°
- Experimental data available for validation
- **Significant improvement** in solution found with iconCFD V5 by increasing max CFL and ramp rate
    - Improvement in convergence
    - Reduction in number of iterations
    - Reduction in drag convergence oscillations
    - Improvement in validation with experiment



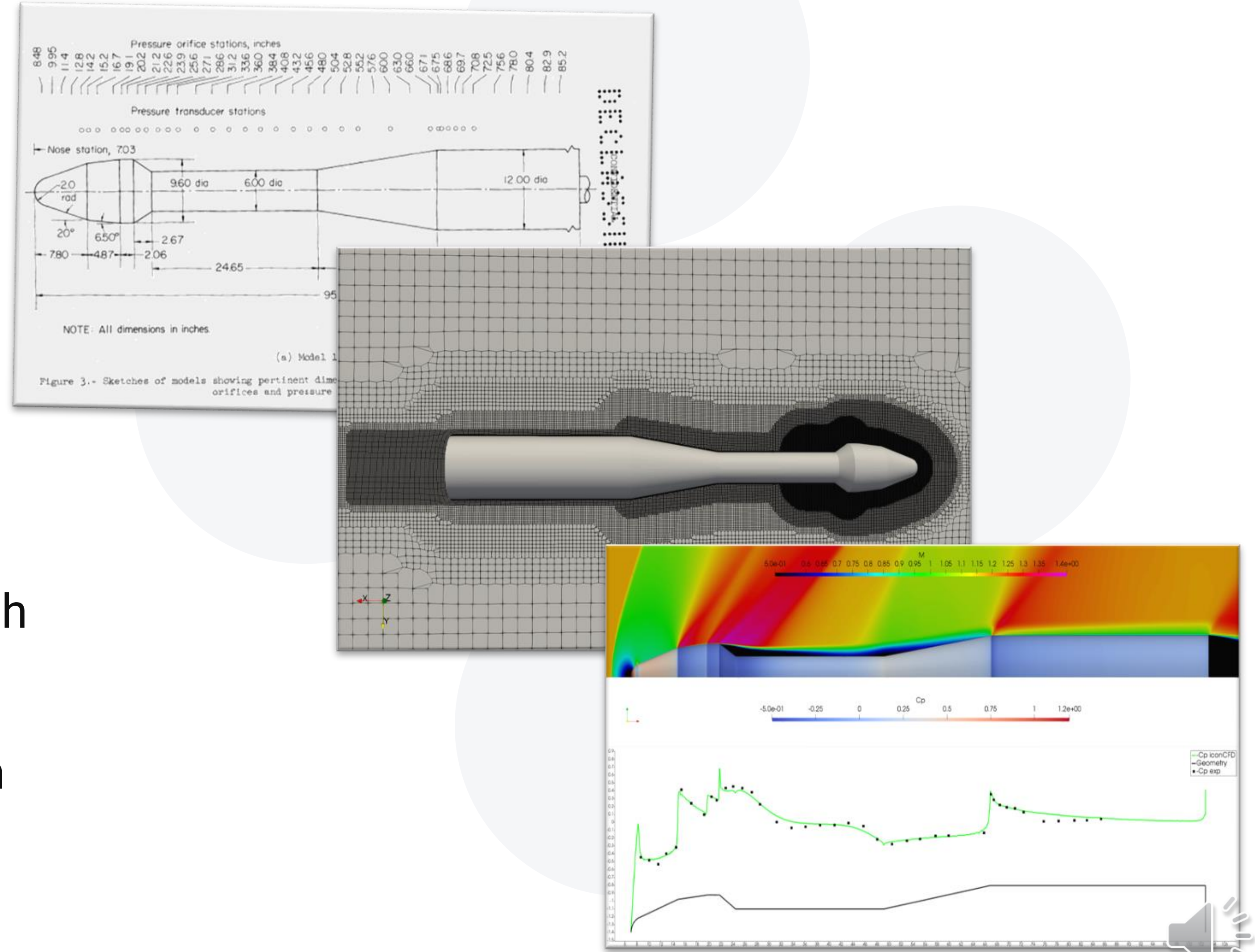


iconCFD version	Total clock time [s]	n iter	Ave. time per iter. [s]	C_d (Exp. 0.0127)	Cauchy criterion on C_d
v4.2.11	156	2000	0.07147	0.012534	4.7973e-6
v5.0.0	108	1000	0.1011	0.012633	6.8457e-7

Validation Results

NASA X778: Transonic Launch Vehicle

- Model 11 of the NASA Tech Memo X778
  - *“Steady and fluctuating pressures at transonic speeds on hammerhead launch vehicles”, NASA -1962*
- Results obtained at Mach 1.17 at 0° angle of incidence
- Half-domain model containing ~5 million cells meshed with iconHexMesh and run on 72 processors
- Previous studies show good validation with experimental data



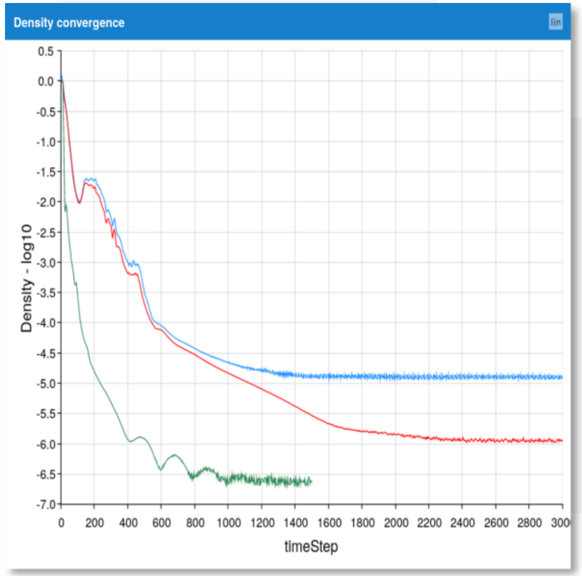
Validation Results

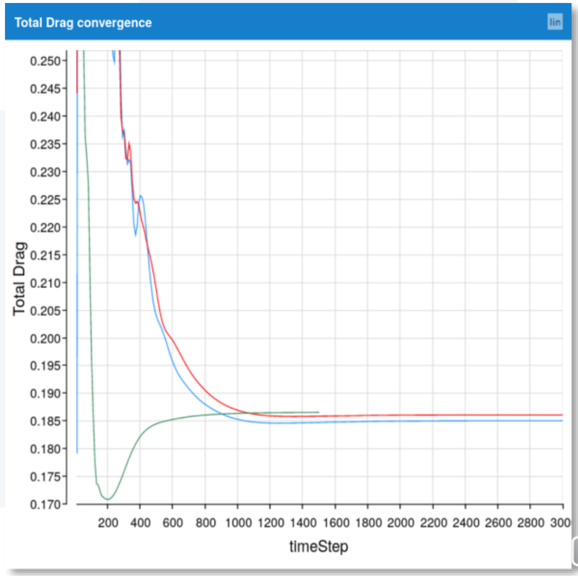
NASA X778: Transonic Launch Vehicle

- iconCFD V4 (v4.2.11) exhibits **32% speed up** for no change in solution compared to baseline version (v4.2.8)
- iconCFD V5 exhibits **improved convergence** for same set up
- Due to improved stability of solver with iconCFD V5, an optimised setup obtains a **further 18% speed up**, which includes:
  - Increasing CFL by a factor of 3
  - Fully 2^{nd} order flux limiting scheme
  - 50% reduction in number of iterations to convergence

iconCFD version	Performance improvement	Total clock time [s]	n iter	Ave. time per iter. [s]	% total speed up vs Baseline
v4.2.8	Baseline	10281	3000	3.388	-
v4.2.11	Parallel comms improvement	6944	3000	2.28	**32.46**
v5.0.0	BC method	7080	3000	2.322	**31.14**
v5.0.0	BC method + Optimised case set up	5807	1500	3.809	**43.52**

v4.2.11
v5.0.0
v5.0.0, optimised set up

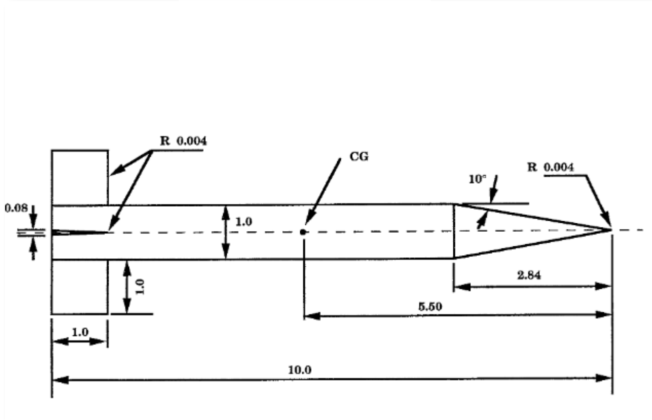


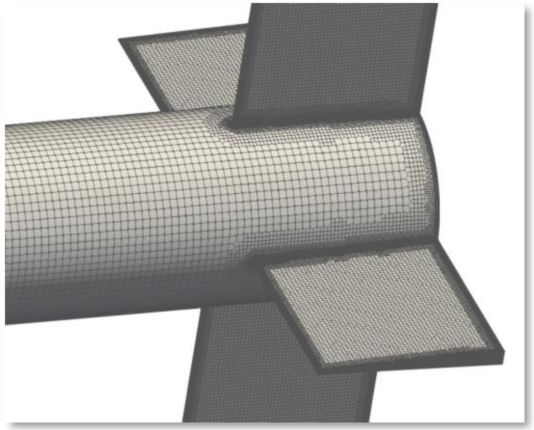
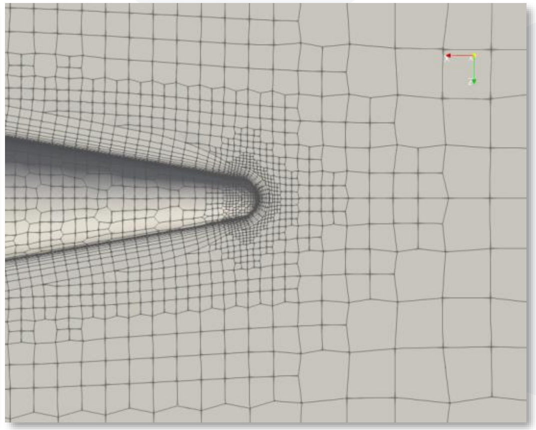
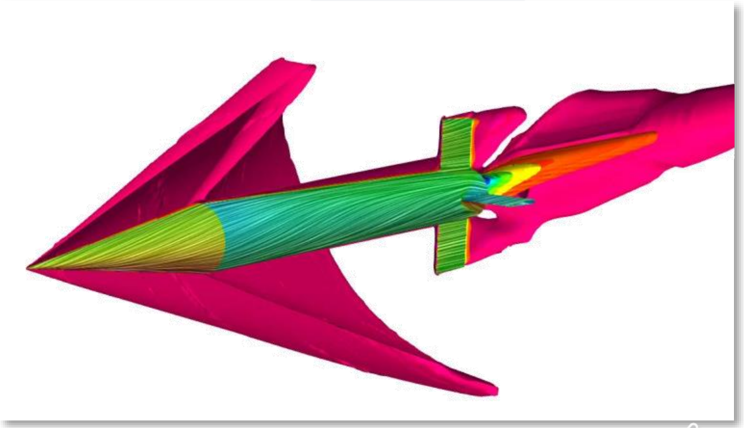


Validation Results

Basic Finner: Supersonic Projectile

- Basic projectile with fins
  - “Aeroballistic range tests of the Basic Finner reference projectile at supersonic velocities” A.D.Dupuis et al. 1997
- Results obtained at a Mach 2.4 at an incidence of 0°
- Half domain model containing ~4.5 million cells meshed with iconHexMesh and run on 64 processors
- y+ ~30 at wall hence case utilises wall functions for turbulent wall treatment

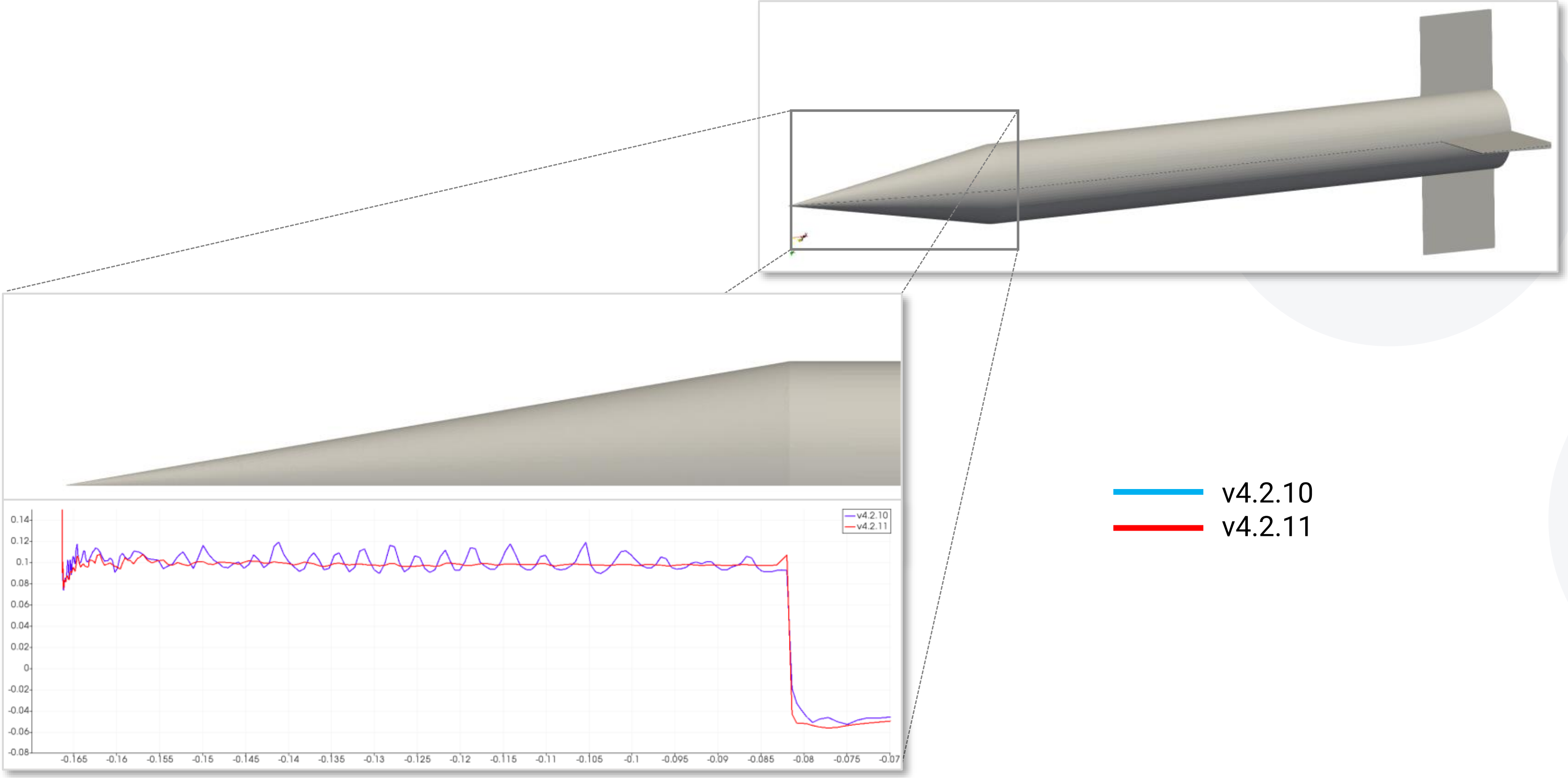


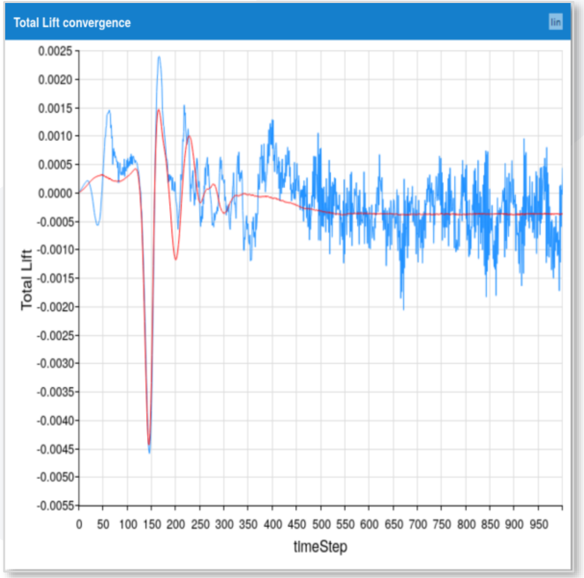
Validation Results

Basic Finner: Supersonic Projectile

- Improved wall function support was applied in iconCFD V4 (v4.2.11)
- Signficant reduction in pressure fluctuations on model surface are found
- This is also evident from the lift convergence behaviour



v4.2.10
v4.2.11

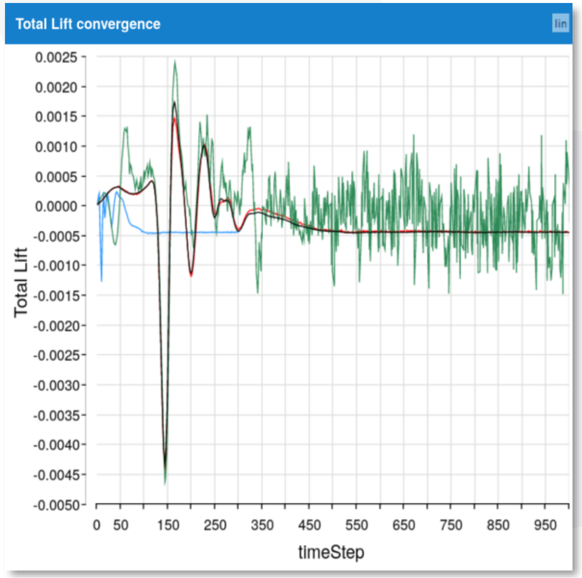


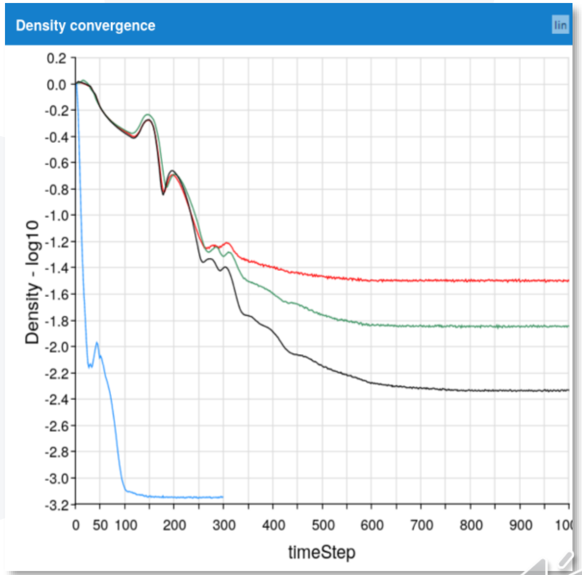
Validation Results

Basic Finner: Supersonic Projectile

- iconCFD V4 (v4.2.11) exhibits a **~31% speed up** due to the parallel improvements
- iconCFD V5 exhibits **improved convergence** for the same case set up
- A **further 35% speed up** is obtained from optimising the case with iconCFD V5 due to **improved stability**
  - Increased max CFL and ramping rate
  - Significant improvement in convergence
  - 70% reduction in iterations

iconCFD version	Performance improvement	Total clock time [s]	n iter	Ave. time per iter. [s]	% total speed up vs Baseline
v4.2.8	Baseline	6982	1000	6.793	-
v4.2.11	Parallel comms improvement	4820	1000	4.651	**30.96**
v5.0.0	BC method	4865	1000	4.699	**30.32**
v5.0.0	BC method + Optimised case set up	2461	300	7.824	**64.75**



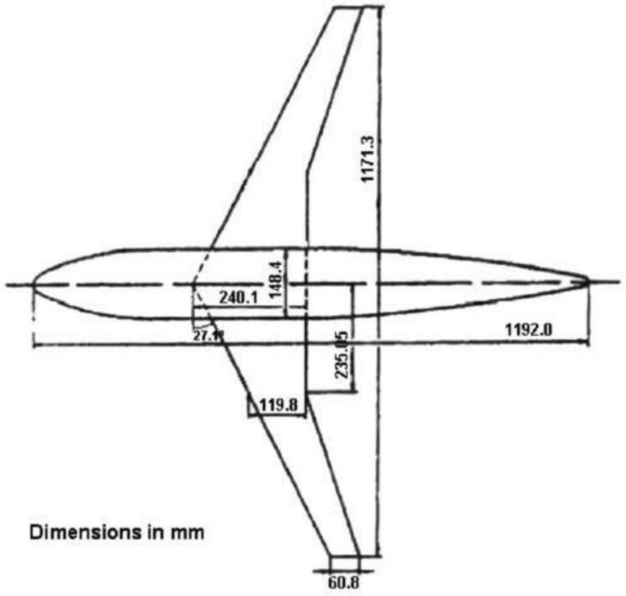


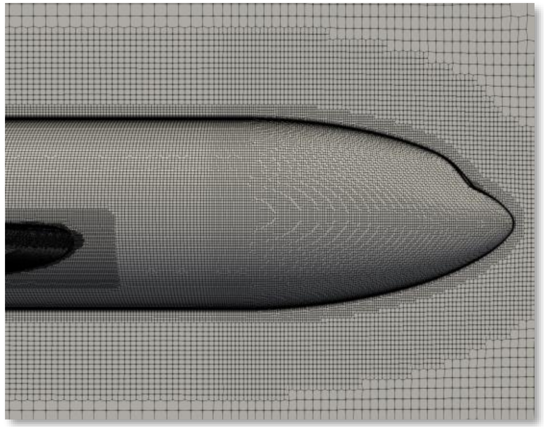
v4.2.8
v4.2.11
v5.0.0
v5.0.0 optimised

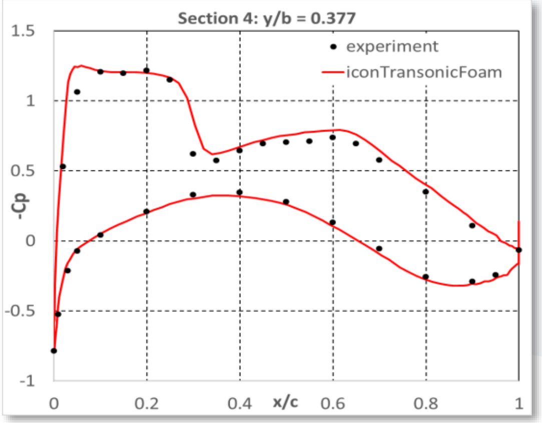
Validation Results

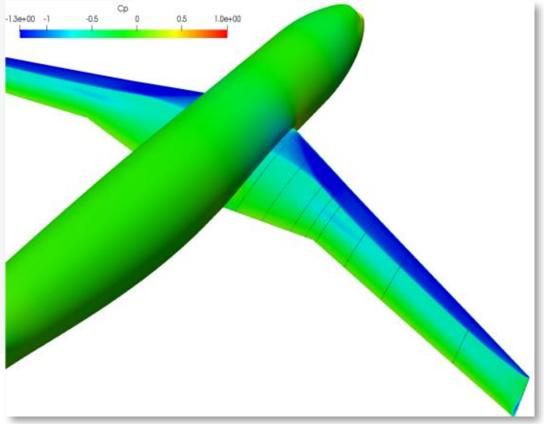
DLR F6: Full Aircraft Configuration

- 3rd AIAA Drag Prediction workshop: DLR F6 Wing-Body configuration without FX2B fairing
- Case 3: fully turbulent, Mach 0.75, Reynolds number 5 million, 0.5° angle of incidence
- Half-domain model containing ~10 million cells meshed with iconHexMesh using the aeroBlockMesh utility to provide an initial anisotropic blocking framework around the geometry







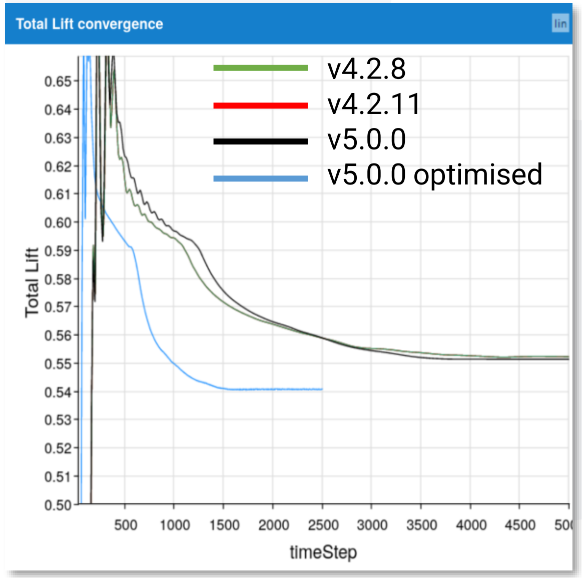


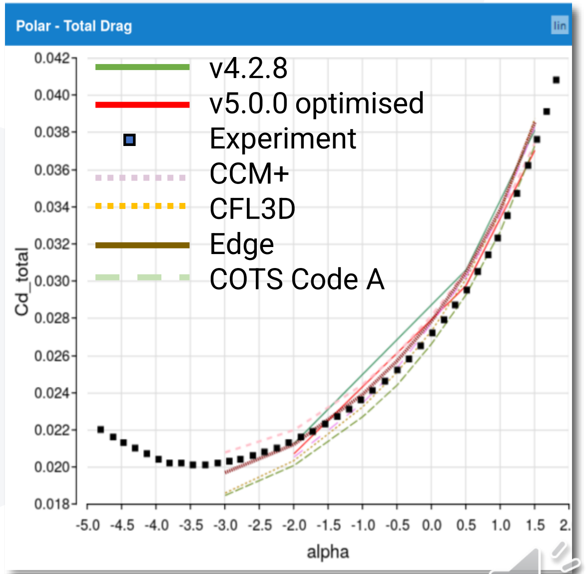
Validation Results

DLR F6 Wing Body: Full Aircraft Configuration

- Parallel improvements in iconCFD V4 (v4.2.11) gives **~43% speed up** but no change in solution compared to baseline version (v4.2.8)
- Small improvement in speed with iconCFD V5 for same case set up
- **Improved stability** of iconCFD V5 allows further case optimisation
  - Increased max CFL and ramping rate
  - BiCGStab linear solver with reduced linear convergence tolerance
  - Local time stepping for turbulence
  - 50% Reduction in time to convergence
  - Improvement in validation with experiment
- iconCFD V5 achieves a significant **~78% speed** up over iconCFD V4 (v4.2.8)

iconCFD version	Performance improvement	Total clock time [s]	n iter	Ave. time per iter. [s]	% total speed up vs Baseline
v4.2.8	Baseline	50765	5000	10.06	-
v4.2.11	Parallel comms improvement	29020	5000	5.733	**42.83**
v5.0.0	BC method	27160	5000	5.363	**46.50**
v5.0.0	BC method + Optimised case set up	11044	2500	4.316	**78.24**

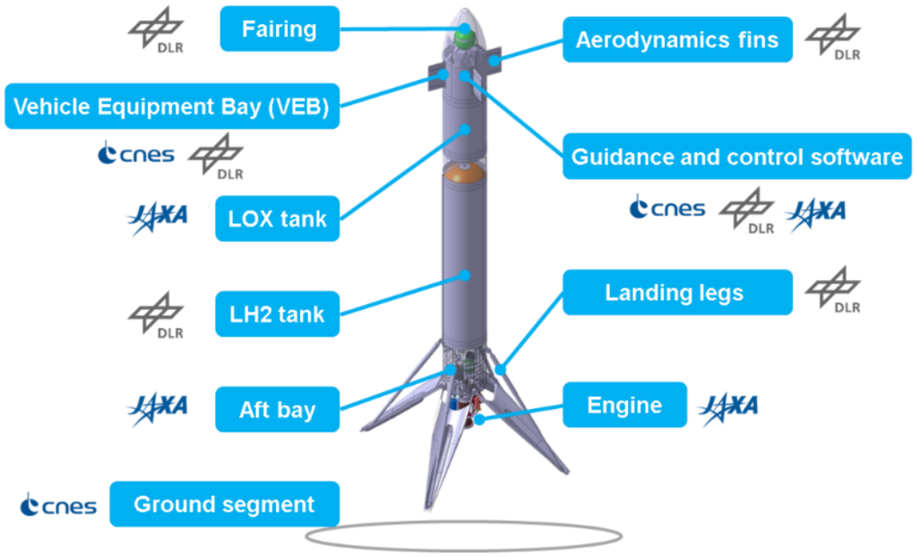




Industrial Case Studies

CALLISTO project

- CALLISTO is a reusable launcher demonstrator developed in collaboration between CNES, JAXA and DLR.
- ICON is providing CFD support for different types of simulation covering the various flight phases, such as lift-off, ascent and re-entry.
- iconCFD V5 is used to run simulations from subsonic to supersonic phases, including the transonic regime.
- Most of the simulations are RANS simulations.
- Some specific flight conditions are reproduced using DES simulations.

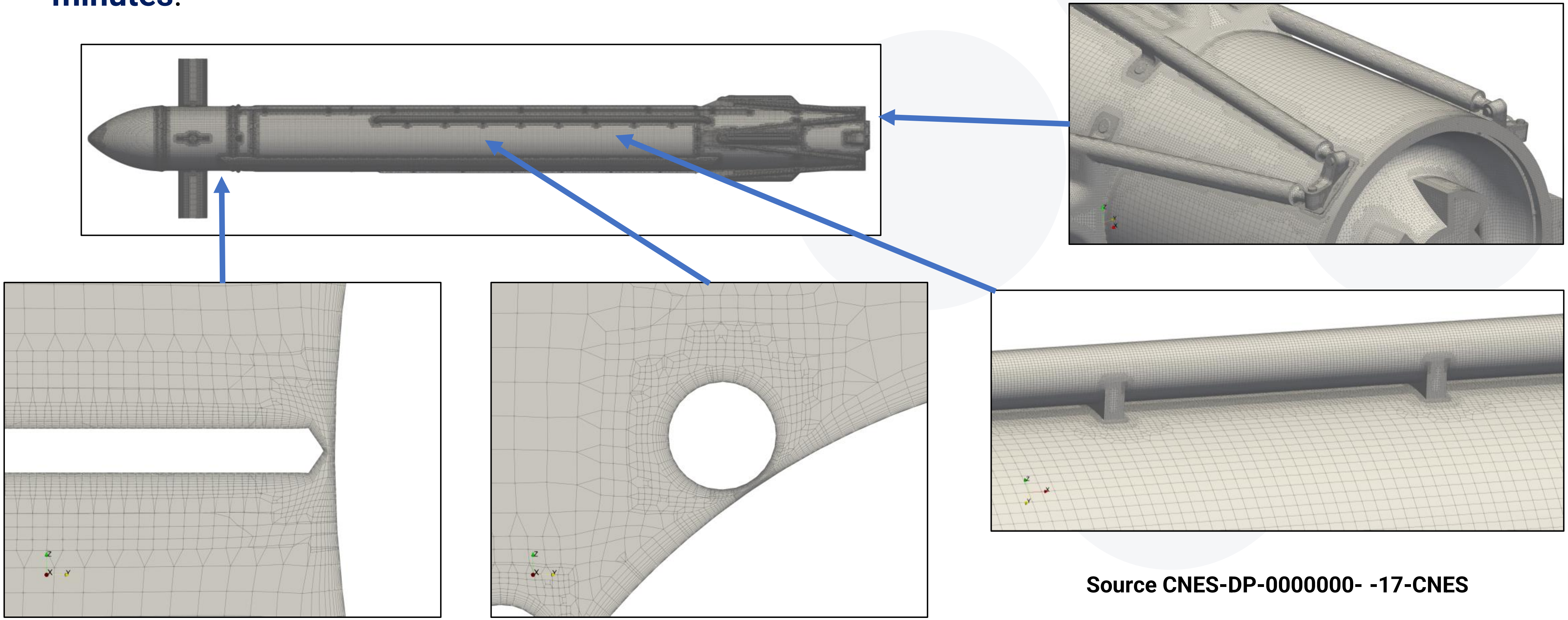


Source CNES-DP-0000000- -17-CNES

Industrial Case Studies

CALLISTO project

- Highly complex geometry, with multiple scales and close proximity of some parts.
- iconCFD is used to generate a **full layer mesh** (y+~1 everywhere) and 50 milion cells **within a few minutes**.

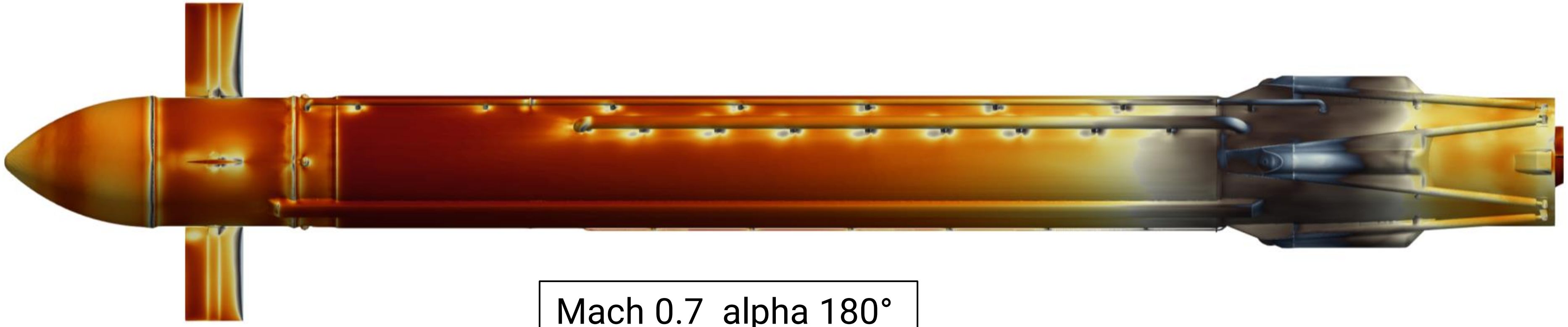


Source CNES-DP-0000000- -17-CNES

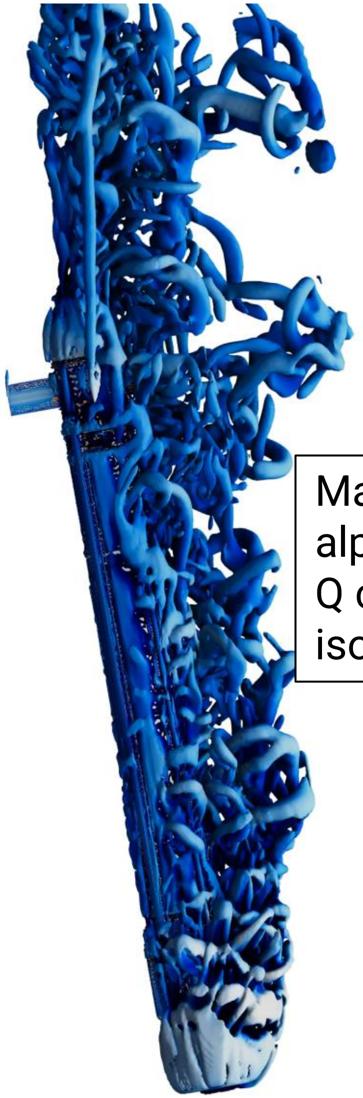
Industrial Case Studies

CALLISTO project

- The DES simulations are run using iconCFD V5.
- The CFD simulations provide more insight than experiments in flow-field
  - Some parameters distribution such as Cp and Cp_rms can eventually be used as input for vibro-acoustic simulations.



Mach 0.7 alpha 180°
Cp_rms distribution



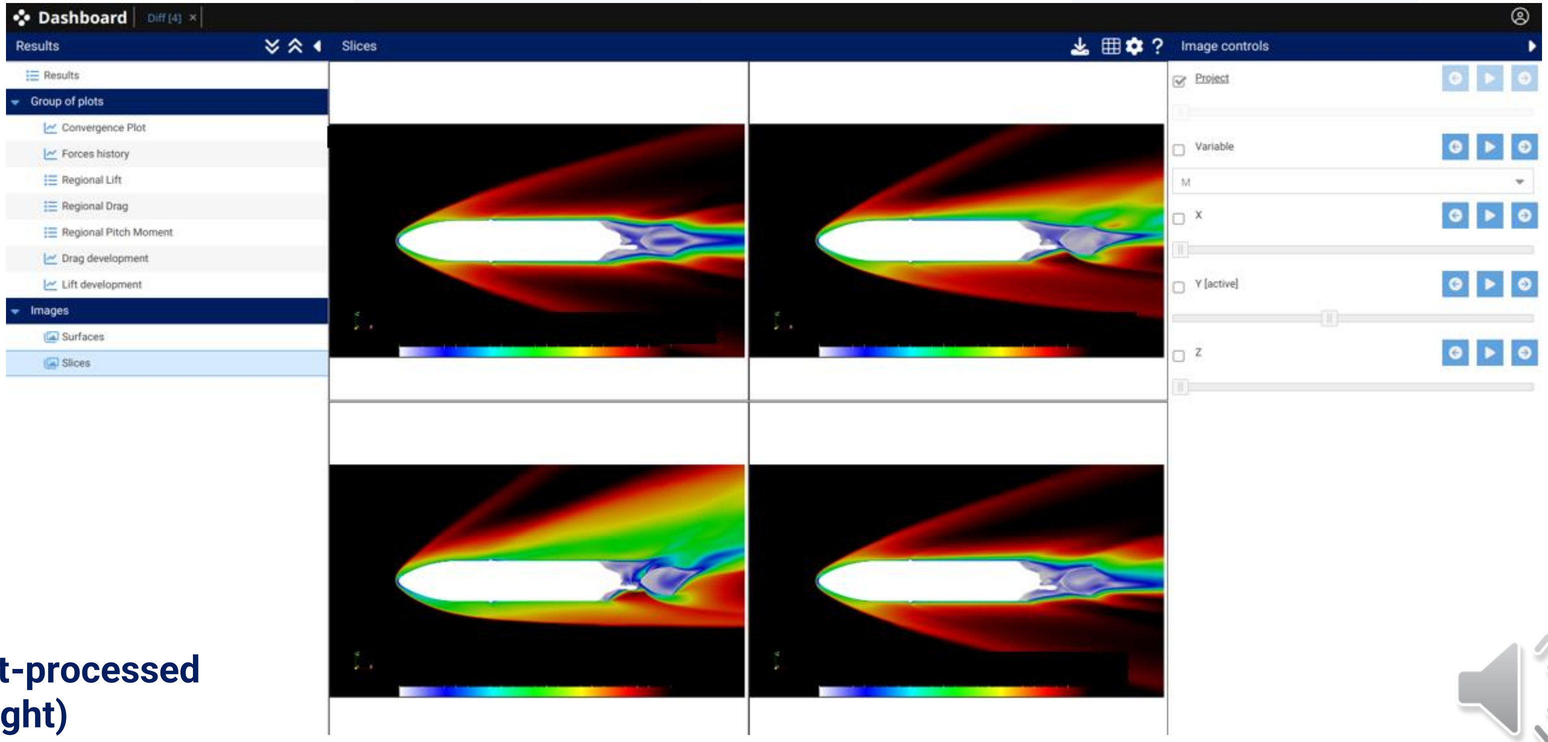
Mach 0.7
alpha 170°
Q criterion
iso-surface

Source CNES-DP-0000000- -17-CNES

Industrial Case Studies

MaiaSpace collaboration

- MaiaSpace is using iconCFD V5 to run RANS simulations with multi-species models on their launchers including engines turned on and off.
- iconPlatform is used to run, analyse, compare hundreds of simulations in order to build aero database of their launchers.



MaiaSpace iconPlatform login page (left) and post-processed results automatically uploaded to iconPlatform (right)

Industrial Case Studies
MaiaSpace collaboration

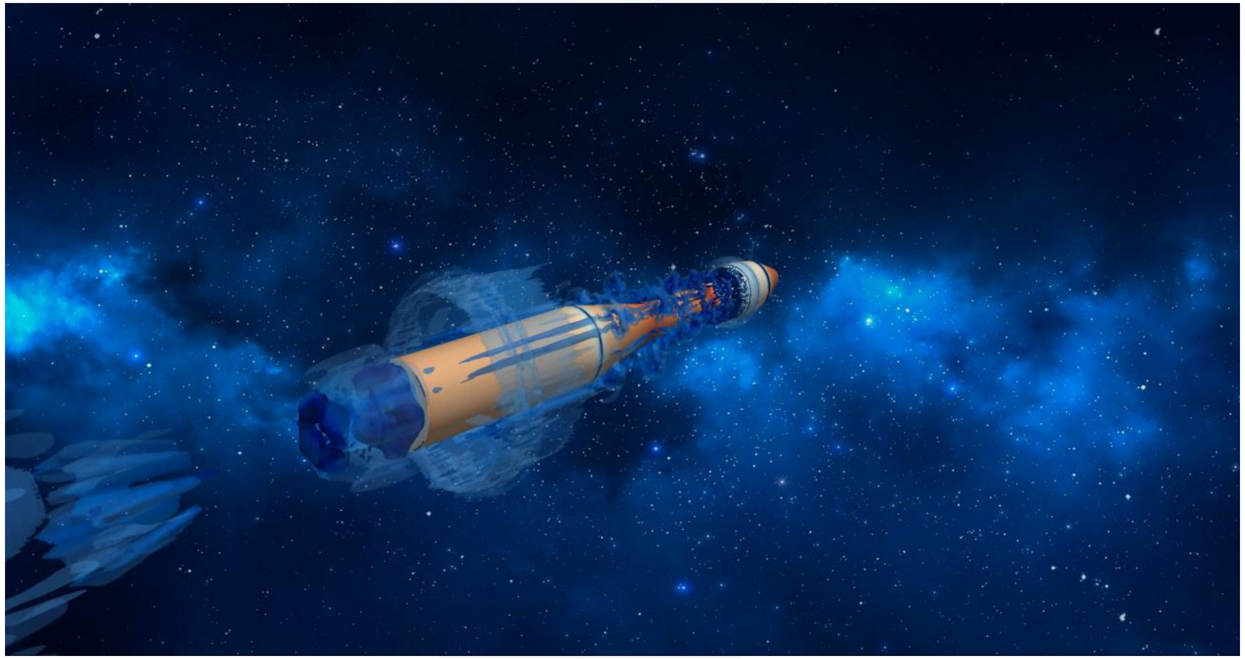
- iconPlatform is leveraging iconCFD capacities by:
  - Automating highly complex meshes of the full launcher.
  - Providing consistent and repeatable simulations setup based on best practices developed by ICON experts.
  - Producing hundreds of data (global coefficients, convergence, surface results, flow field images) automatically for each case and organising them so that they can be easily compared.

MaiaSpace reusable launcher, ~50m cells, RANS, M=2, iconCFD V5

Conclusions

Summary

- iconCFD V5 contains a significantly enhanced density-based coupled solver which converges at a faster rate and to a lower residual level
- Enhanced stability in iconCFD V5 also allows to run more complex cases, to converge further and to provide more accurate solutions
- Enhanced wall treatment behaviour provides superior stability for high y+ meshes and improved parallel communications delivers better and faster performance
- iconCFD V5 is successfully being used for industrial applications in collaboration with industrial partners for a range of launch vehicle simulations for different flight phases such as lift-off, ascent and re-entry with engines on and off over a range of flight regimes from subsonic to transonic to supersonic
- iconPlatform has been used to store all post-processed data (and submit runs to HPC) to facilitate data organisation and analysis for all simultation data



NASA X778 launch vehicle, ~27m cells, SADDES, M=0.8, iconCFD V5

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