Can you trust your CFD simulation?

Cavity study - understand, reproduce, compare

CFD / FIELD NOTES
E001 · 0.6

Can you trust this simulation?

Carsten Püttbach

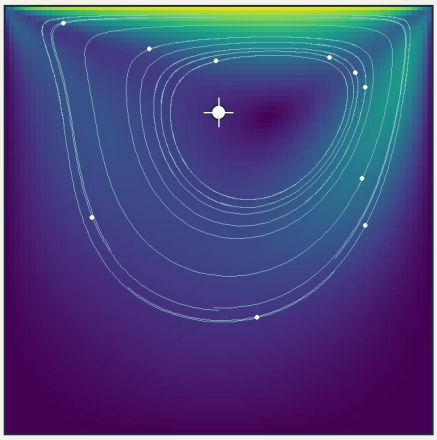
CFD practitioner

Product development lead

Curiosity

Clear models

Careful checks



AI narration · scientific work by Carsten and this project

Frozen computed field · direction markers · |u|/U: 0–1

C01 · Author biography supplied by Carsten: CFD practitioner and head of product development

A practical companion to the English film by Carsten Püttbach. Work through a small open-source problem before applying the same habits to more complex geometry, pressure losses, or thermal flows.

You will practise controlled comparisons, physical sampling, mesh and time sensitivity, and the interpretation of numerical references. This is an educational benchmark, not validation of a real valve or thermal device.

Start with two quick cases. The full eight-mesh study and the finest-grid time check require substantially more computation. The film uses precomputed results to keep that waiting time out of the explanation. Sources: S01, S04, C01.

1 / Define the question

Your output is part of your model

For the baseline mesh study we ask: how does horizontal velocity at (x/L, y/L) = (0.5, 0.75) respond to mesh refinement at the same physical time? We also inspect centreline profiles and an interpolated primary-vortex velocity zero.

Quantity	Meaning / value
L	Cavity width: 0.1 m
U	Lid speed: 1 m/s
nu	Kinematic viscosity: 0.001 m2/s
Re = UL/nu	100
t / t*	1 s / 10 for the finite-time eight-mesh comparison
Horizontal probe	u/U, at (0.5L, 0.75L)

Model: 2D, incompressible, Newtonian laminar flow with constant properties; no energy equation, phase change, free surface or extra body force. This does not represent water at a stated temperature. The empty front/back patches enforce the 2D setup.

Task: name an engineering output you would need for a real design decision, and a justified tolerance. Avoid picking a tolerance only because the computed differences happen to be small. Sources: S01-S04.

Your prediction / observations

2 / Run your first comparison

Tested environment: OpenCFD v2606 native Mac app

Extract E001_Companion_Cases.zip and open a terminal in its E001_Companion_Cases folder. FreeCAD is not needed for this block-defined square. No package installation or account is performed by the supplied scripts.

```
zsh run_on_mac.sh
python3 analyse_demo.py
```

The Mac helper uses the documented app at /Applications/OpenFOAM-v2606.app. In an already configured OpenFOAM environment, you can instead run:

```
python3 run_demo.py --meshes 10 20
python3 analyse_demo.py
```

The runner uses the Python standard library. Analysis requires NumPy, already available on the production Mac. Other OpenFOAM branches or versions may need different dictionaries; do not mix their instructions silently.

Stage	What to expect
blockMesh	Generate the mesh from the block description
checkMesh	Read the log and require Mesh OK
icoFoam	Solve to t = 1 s
postProcess	Write actual cell centres
analyse_demo.py	Verify layout; write profiles.csv and probe-results.csv

Every run receives a new timestamped directory. On failure, inspect logs; do not delete evidence or overwrite a previous result. The short N10/N20 path was replayed and checked against the production measurements. Source: S01.

Your prediction / observations

3 / Know the case files

File	Role
system/blockMeshDict	Geometry, cell counts, patch topology
0/U	Velocity initial and boundary conditions
0/p	Kinematic pressure and its boundary conditions
constant/transportProperties	Kinematic viscosity
system/fvSchemes	Euler time derivative; linear face/gradient reconstruction; orthogonal Laplacian
system/fvSolution	Linear solvers; pressure/velocity correction controls
system/controlDict	Start, end, time step, saved results

The moving lid has fixed velocity (1, 0, 0). Other walls use no slip. The pressure reference fixes a gauge; it does not establish an experimentally measured absolute pressure. In this case stored p has units m2/s2, corresponding to physical pressure divided by constant density.

Make a prediction: if you move a boundary, change viscosity or change the mesh, which part of the mathematical problem or approximation changes? Keep that classification with the case. Sources: S01, S03, S13.

Your prediction / observations

4 / Compare eight meshes

```
python3 run_demo.py --meshes 10 20 30 40 60 80 120 160
python3 analyse_demo.py
```

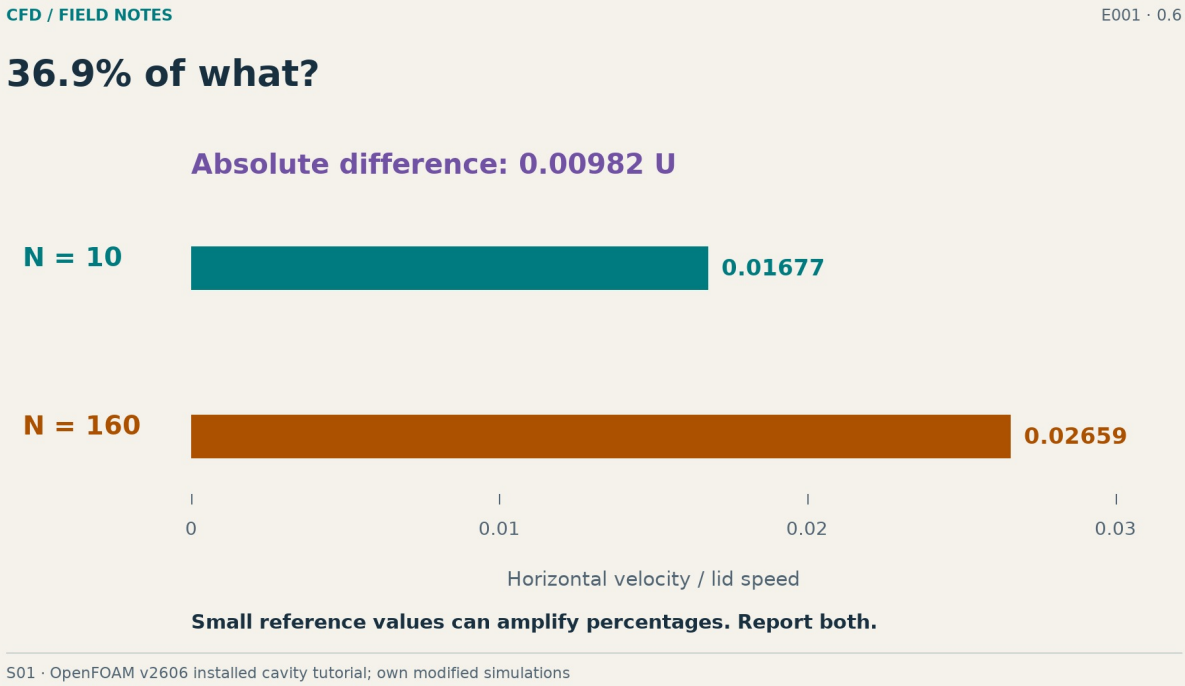
N	Cells	h/L	u/U at probe, t = 1 s
10	100	0.100000	0.01677281
20	400	0.050000	0.02022140
30	900	0.033333	0.02262975
40	1600	0.025000	0.02489768
60	3600	0.016667	0.02593580
80	6400	0.012500	0.02627988
120	14400	0.008333	0.02651235
160	25600	0.006250	0.02659017

Keep nu, U, L, initial/boundary conditions, dt = 0.00025 s, solver controls and final time fixed. Doubling N gives four times as many cells in this 2D study; it does not guarantee a particular runtime multiplier.

Use the same physical probe and interpolation method on every mesh. A nearest-cell sample may move as N changes. N160 is a comparison baseline, not exact truth. Refinement may affect different quantities differently. Sources: S01, S02, S09.

Your prediction / observations

5 / Read differences honestly



The N10 value is 36.92% below the N160 value at the chosen probe. The absolute difference is 0.00981736 U.

The denominator is the fine-grid probe velocity, not the lid speed. Near a velocity zero, a relative percentage can become especially large. Report absolute and relative differences together and identify the reference.

The primary-vortex position is a rotating velocity zero of a bilinear interpolant. Its movement is about 1.264% L from N10 to N160 and 0.0140% L from N80 to N160. It is not a Lagrangian attractor or a proof of full-field accuracy. Sources: S01, S09.

Your prediction / observations

6 / Understand one approximation

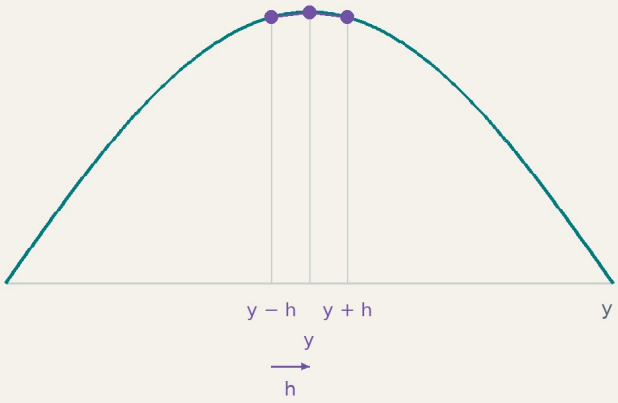
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Same equation. A different approximation.

ANALYTIC ILLUSTRATION · not cavity data

$$\phi(y) = \sin(\pi y)$$



$$D_h^2\phi = \frac{\phi(y+h) - 2\phi(y) + \phi(y-h)}{h^2}$$

At y = 0.5

$$\phi'' = -\pi^2$$

h = 0.0625

D²φ ≈ -9.8379

0.32% difference

In the cavity, several numerical operators interact.

S11 · Analytic central second difference applied to sin(pi y)

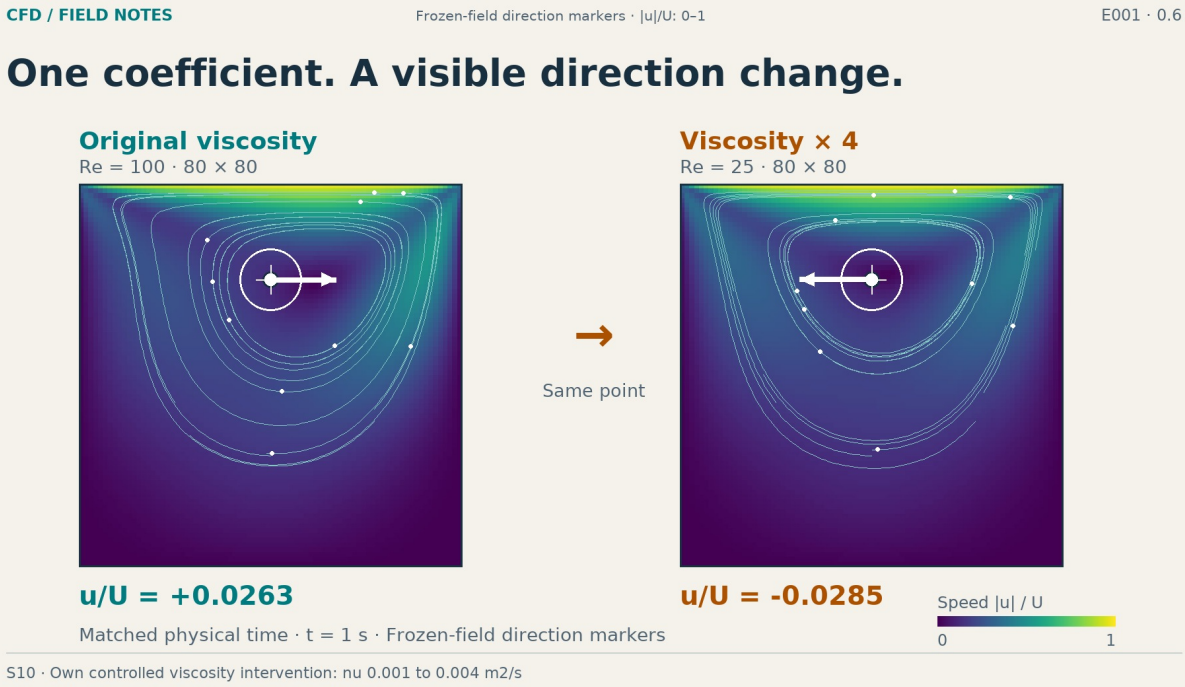
```
phi(y) = sin(pi*y)
D2_h phi = [phi(y+h) - 2*phi(y) + phi(y-h)] / h^2
phi_second(y) = -pi^2 * sin(pi*y)
```

At y = 0.5, compare the direct three-sample evaluation against -pi squared. The relative magnitude difference is 5.03588% at h = 0.25 and 0.320864% at h = 0.0625. The ratio is [sin(pi*h/2)/(pi*h/2)] squared.

This smooth scalar interior-point illustration explains one operator. It does not isolate total cavity error. Finite volume fluxes, pressure coupling, other discrete operators, and the abrupt lid corners all require their own interpretation. Sources: S11, S12.

Your prediction / observations

7 / Change viscosity, deliberately




```
python3 run_demo.py --meshes 80 --nu 0.004
```

Against a matched N80 baseline, the viscosity input rises by four and Re falls from 100 to 25. Match all other inputs and compare at t = 1 s. The production check verified the entire input tree: only the viscosity coefficient differs.

The same probe gives u/U = +0.02627988 before and -0.02847468 after. This local reversal is a measured response of the coupled calculation. It is not a universal rule about increasing viscosity.

Use equal colour limits and camera orientation. Moving direction markers and a wipe compare frozen fields; neither is a physical particle trajectory. Sources: S03, S10.

Your prediction / observations

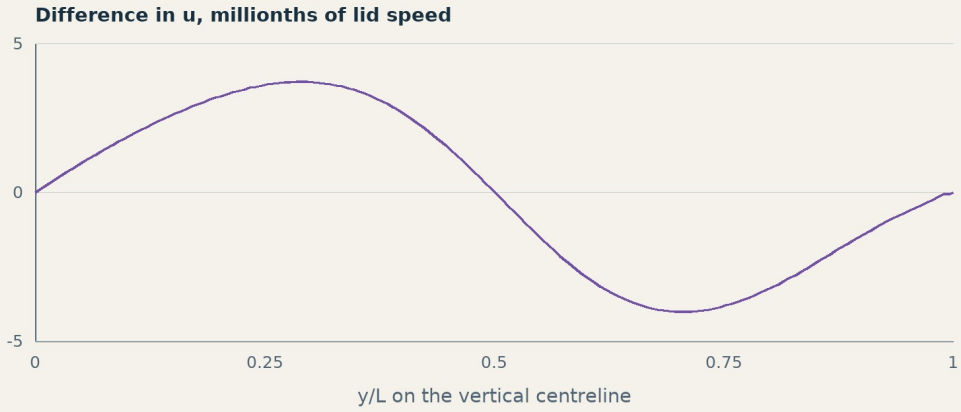
8 / Check the finest time step

```
python3 run_demo.py --meshes 160 --dt 0.000125
```

CFD / FIELD NOTES

E001 · 0.6

Check time spacing on the finest grid.



Field-vector RMS difference: 56.3 × 10⁻⁶ U · t = 1 s · N = 160

S15 / S16 · Greenshields & Weller: Time discretisation

Compare both N160 runs from initial rest at t = 1 s. The root mean square magnitude of the velocity-vector difference across cells is 56.28 millionths of U. It is not the RMS of two separately counted scalar components.

A Courant-number limit is a useful case control, not a universal accuracy certificate. The production runner stops acceptance at max Co >= 0.5. That is a conservative project choice, not a rule prescribed for every CFD solver. Two time steps demonstrate sensitivity; they do not establish a temporal convergence order. Sources: S15, S16.

Your prediction / observations

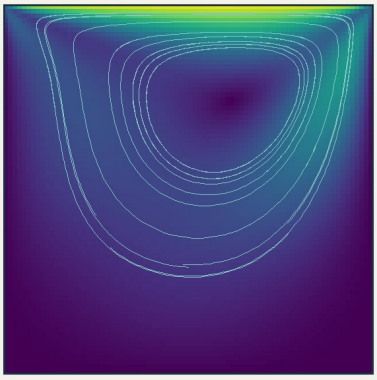
9 / Check temporal settling

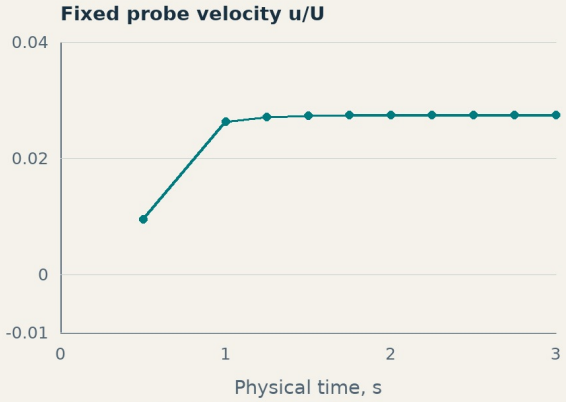
CFD / FIELD NOTES

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Make “settled” a measurable statement.

Saved CFD field · t = 3 s





N40 / N80 / N160: field-change screen passed

Actual saved snapshots · replay speed differs from simulation time

S14 / S16 · NASA/NPARC: Examining Iterative Convergence

N	RMS vector change / U, t2.5 to t3	Episode criterion
40	2.110e-07	<= 1e-5
80	2.204e-07	<= 1e-5
160	2.361e-07	<= 1e-5

All three fields meet the predeclared screen over the tested interval. This is a practical decision for this lesson, not an infinite-time proof of a steady state. The production continuation restarts each case at t1; the portable --end 3 command starts at rest.

A low pressure-solve residual addresses the algebraic solve. Mesh resolution, physical model suitability and physical validation remain separate questions. Sources: S14, S16.

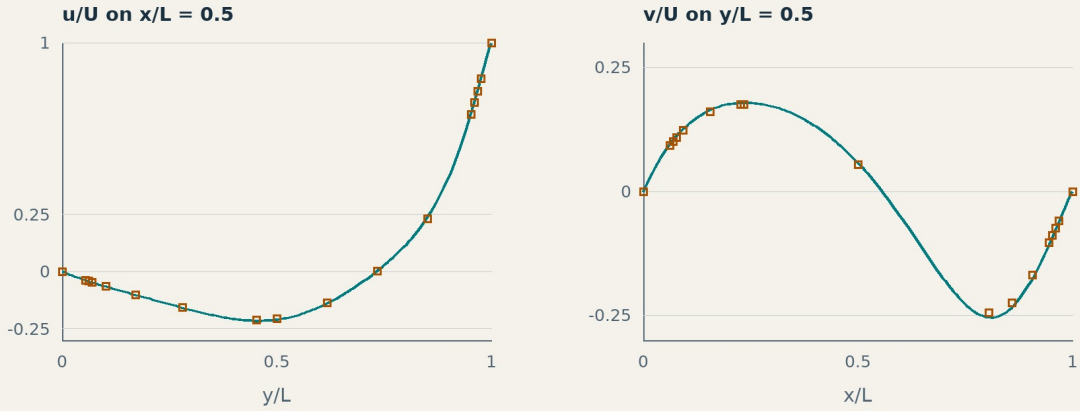
Your prediction / observations

10 / Read the historical reference

CFD / FIELD NOTES

E001 · 0.6

Compare the same quantities at the same points.



Line: own N160 at t = 3 s **Squares: Ghia et al., Re100**

Independent numerical reference · not experimental validation

S05 / S16 · Ghia, Ghia & Shin (1982), Tables I and II, Re100

Ghia et al. Re100 values were visually transcribed from the original Tables I and II, printed pages 398-399. Both components are compared at their printed coordinates. The largest N160 difference across those samples is 0.926% of U.

Some differences grow slightly as our own mesh is refined. Do not hide them or relabel the reference as exact truth. The next page checks selected extrema against a second original numerical reference.

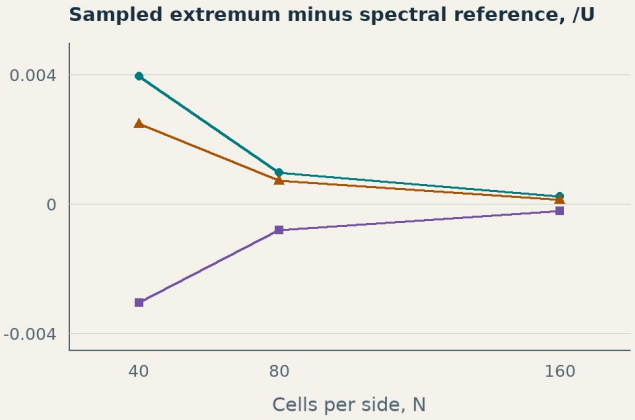
A numerical benchmark is not an experiment. Matching Re alone is insufficient: check geometry, boundaries, normalisation, orientation, stationarity and the measurement definition. Sources: S05, S16.

Your prediction / observations

11 / Check the reference, too

CFD / FIELD NOTES
E001 · 0.6

Check the reference, too.



Botella & Peyret · Re100

● **u minimum: -0.2140424**

■ **v maximum: +0.1795728**

▲ **v minimum: -0.2538030**

Reference lid direction reflected. Our extrema are sampled values.

A numerical reference has its own resolution, method and conventions.

S05 / S18 / S16 · Ghia, Ghia & Shin (1982), Tables I and II, Re100

N	sampled u min	sampled v max	sampled v min
40	-0.2100718	+0.1765245	-0.2513083
80	-0.2130511	+0.1787772	-0.2530542
160	-0.2137931	+0.1793800	-0.2536609
Spectral	-0.2140424	+0.1795728	-0.2538030

Botella and Peyret Table 2 reports converged spectral extrema at Re100. Their lid moves left. For our right-moving lid: x_ours = 1 - x_ref, u_ours = -u_ref, v_ours = v_ref. The values above use that mapping.

Our extrema are sampled on interpolated centrelines. They approach this reference under refinement, but no subcell extremum accuracy or exact physical truth is claimed. Ghia-profile differences and this extrema comparison are different metrics. Source: S18, checked against original PDF pages 2 and 4.

Your prediction / observations

12 / A review you can repeat

Check	Evidence to retain
Question	Quantity, coordinates, normalisation and decision tolerance
Model	Physical assumptions, properties and boundaries
Mesh	Quality diagnostics and relevant spatial sensitivity
Time / solve	Time-step comparison, stationarity criterion, residual and continuity interpretation
Reference	Original source, conventions, matching quantities and limitations
Reproduction	Inputs, logs, fields, hashes, analysis and expected outputs

Verification concerns solving the mathematical problem correctly enough for the intended use. Validation concerns agreement with physical reality, supported by appropriate experimental evidence and uncertainty information. This educational study does not claim formal ASME V&V; 20 conformity or device validation.

Self-check: Why can a small residual coexist with a mesh-sensitive probe? Why can a large percentage correspond to a small absolute difference? Why does benchmark agreement not validate a real valve? Answers: algebraic solve versus discretisation; small reference denominator; numerical evidence versus physical evidence. Sources: S02, S04, S14, S17.

Your prediction / observations

Sources and evidence

S01 / OpenFOAM v2606 installed cavity tutorial; own modified simulations

case provenance, actual numerical measurements Open primary source

S02 / NASA/NPARC: Examining Spatial (Grid) Convergence

grid studies and limitations of convergence claims Open primary source

S03 / Greenshields & Weller: Notes on CFD, incompressible flow

governing equations and incompressible assumptions Open primary source

S04 / NASA/NPARC: Overview of Verification and Validation

verification versus validation Open primary source

S09 / Own primary-vortex centre analysis; piecewise bilinear velocity-zero estimate

instantaneous centre estimate at t*=10; not a physical attractor or exact solution Own case, source inspection, analytic derivation or author statement.

S10 / Own controlled viscosity intervention: nu 0.001 to 0.004 m2/s

Actual N80 finite-time case; input and result hashes in viscosity-case.json Own case, source inspection, analytic derivation or author statement.

S11 / Analytic central second difference applied to sin(pi y)

Exact trigonometric derivation in production guide; not cavity measurements Own case, source inspection, analytic derivation or author statement.

C01 / Author biography supplied by Carsten: CFD practitioner and head of product development

Author wording and likeness review remain human release checks. Own case, source inspection, analytic derivation or author statement.

Sources and evidence / continued

S05 / Ghia, Ghia & Shin (1982), Tables I and II, Re100

Original PDF pages 12/13 visually checked; independent numerical reference, not experiment. Open primary source

S12 / Greenshields & Weller: finite volume concept

Conceptual flux illustration; not measured face fluxes. Open primary source

S13 / Installed OpenCFD v2606 icoFoam.C

PISO loop, pressure correction and required kinematic pressure read from the actual installed source. Own case, source inspection, analytic derivation or author statement.

S14 / NASA/NPARC: Examining Iterative Convergence

Residuals and engineering outputs require interpretation. Open primary source

S15 / Greenshields & Weller: Time discretisation

Euler time approximation and contextual Courant-number interpretation. Open primary source

S16 / Own additional stationarity, time-step and numerical-reference checks

Actual isolated runs, field hashes and publication-evidence.json. Own case, source inspection, analytic derivation or author statement.

S17 / ASME V&V 20-2009 (R2021), official overview and contents

Overview and contents inspected; full licensed standard not reviewed. No conformance/certification claim. Open primary source

S18 / Botella & Peyret (1998), Re100 spectral extrema, Table 2

Original pp. 2/4 visually checked; left-moving reference lid reflected for our right-moving lid. Sampled extrema, not exact physical truth. Open primary source