Two-day meeting on Propulsion simulation using OpenFOAM Technology, Milan

RANS simulation and validation of full-scale internal combustion engine under motored condition.

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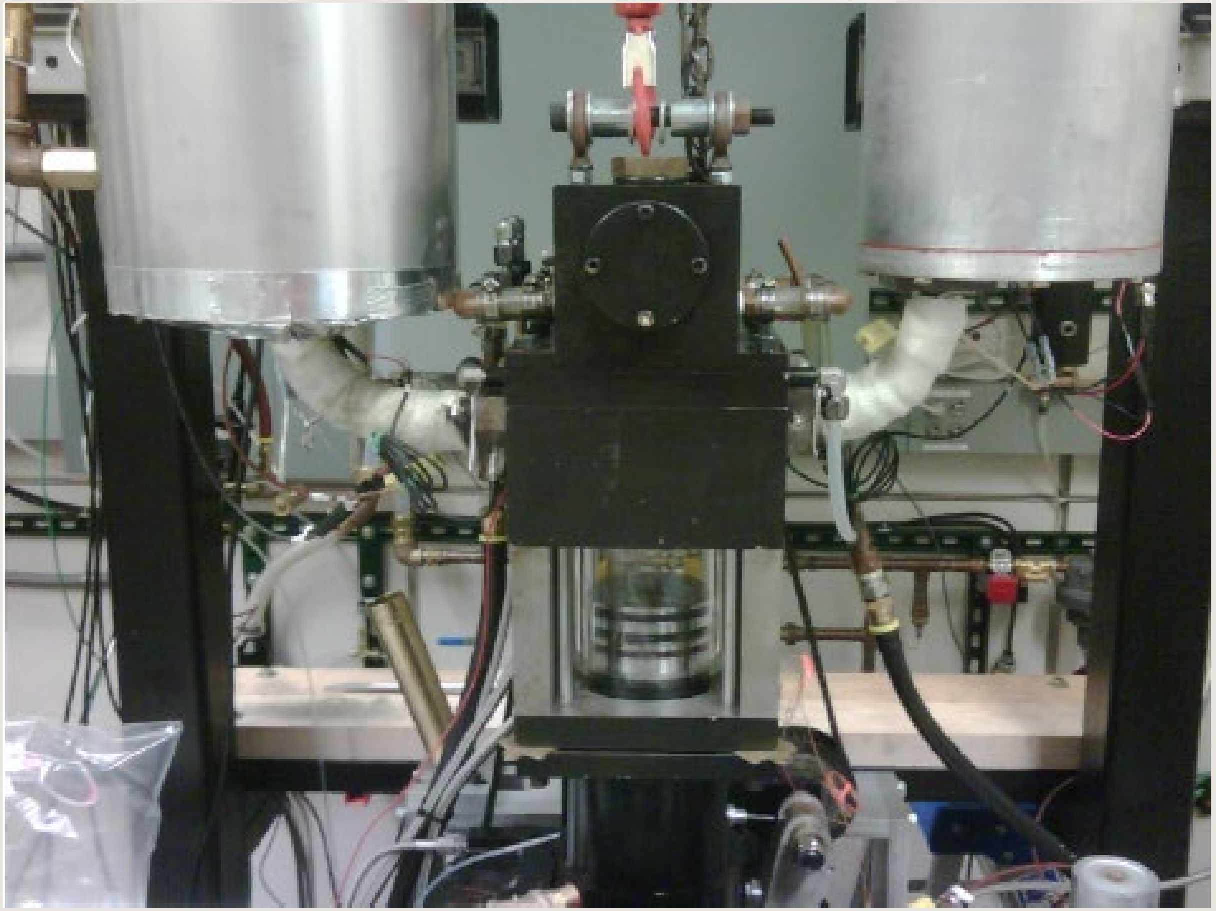
Objectives

- To create an IC engine model setup for motored condition in OpenFOAM, that can be used for easy benchmarking of CFD methodologies.
- To validate simulation results against optical engine process and flow field data.
- To compare results from commercial and open-source meshing solutions.
- Making the setup publicly available, resembling a plug-and-play template for IC Engines.

Selection of the Engine

Parameters	Transparent Combustion Chamber (TCC)-III
Engine geometry data	Publicly available [6]
Experimental data	Publicly available [6]
Geometry simplicity	Simple geometry - 2 valve, flat cylinder head and flat piston
Boundary condition data	GT power, transient boundary condition available [6]

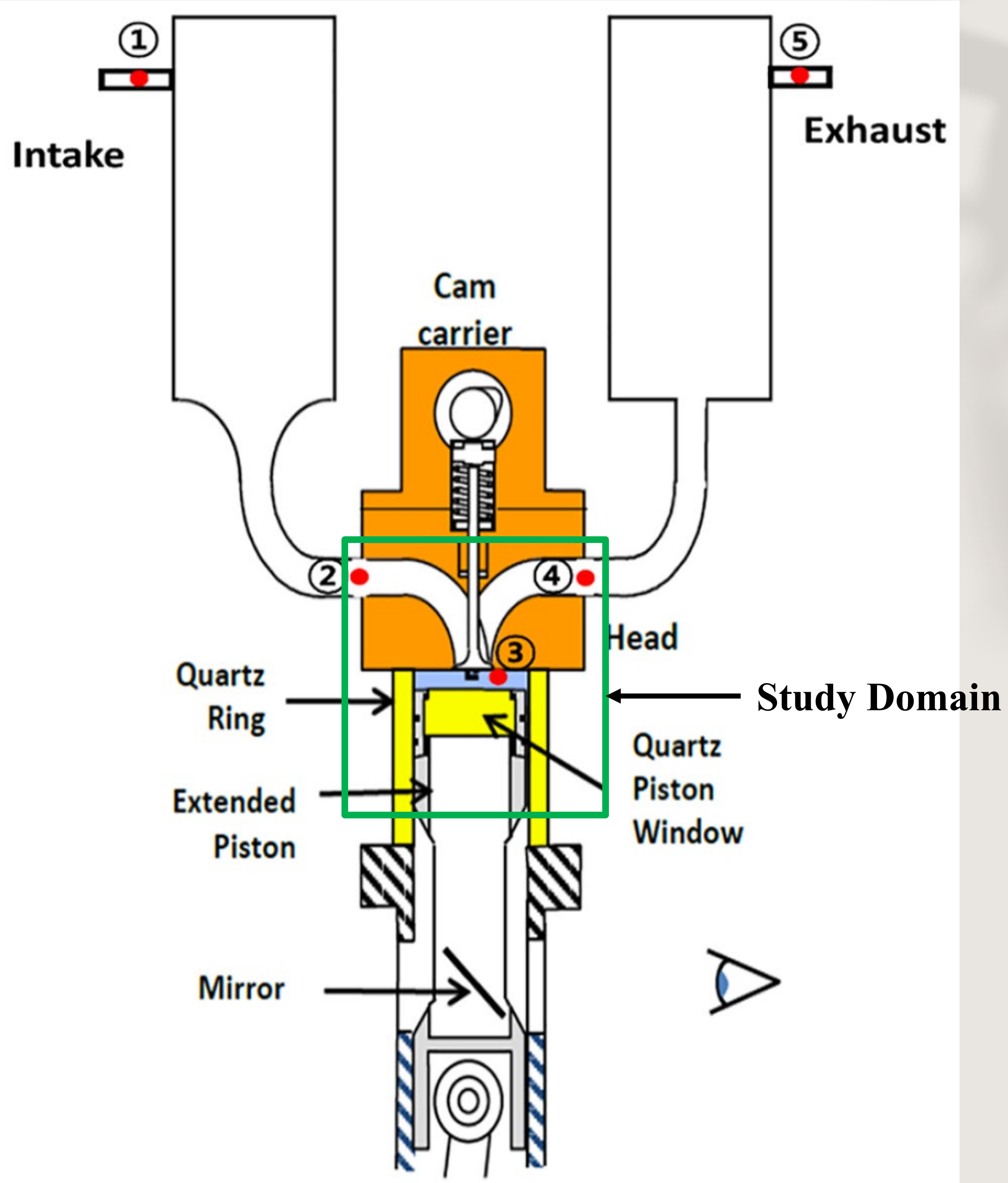


The TCC-III engine at University of Michigan.

6: https://deepblue.lib.umich.edu/data/collections/8k71nh59c

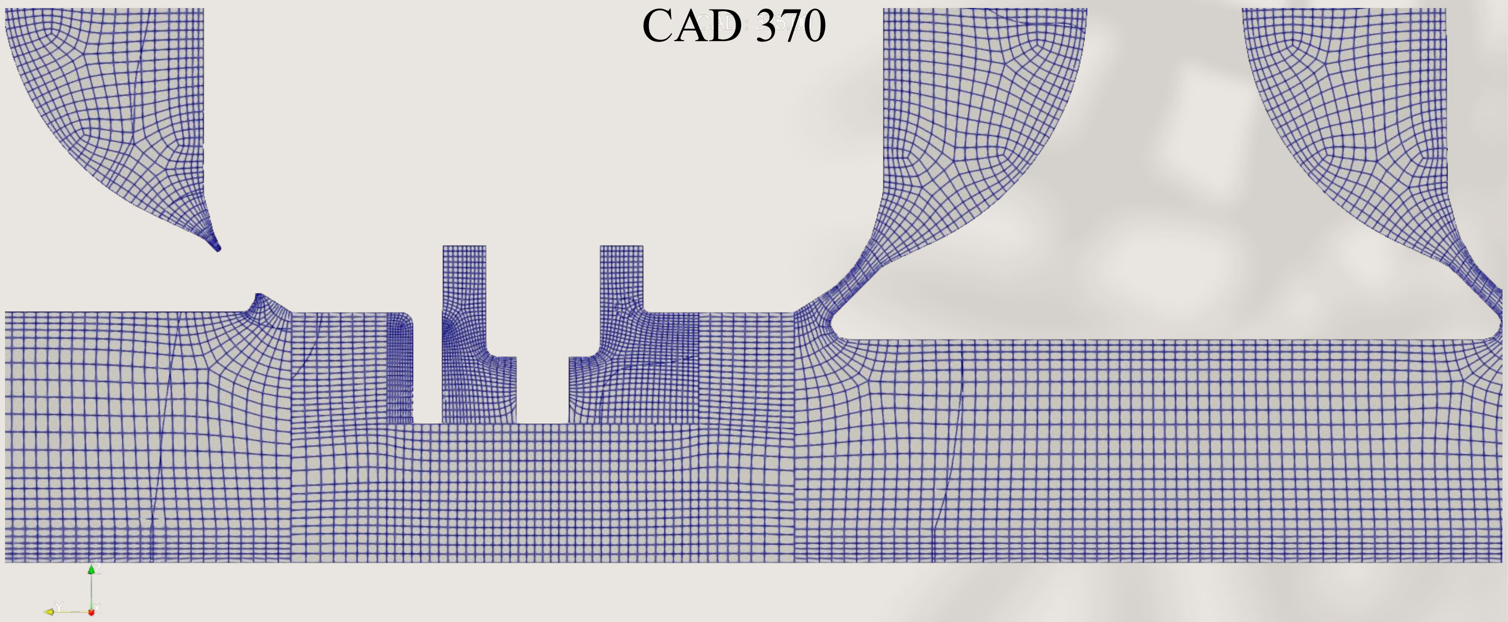
TCC - III

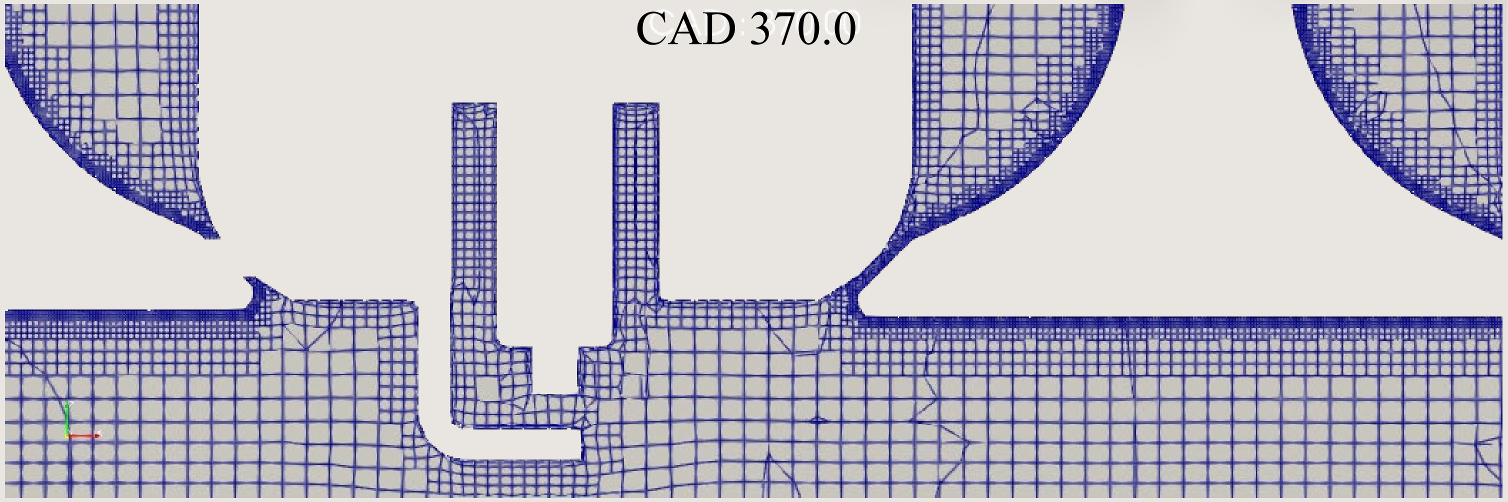
- Transparent Combustion Chamber (TCC) is an optical engine developed at University of Michigan.
- 4-stroke, 2-valve, 800 rpm, Spark Ignited, 10:1 compression ratio with flat combustion chamber and flat piston.
- Bore x Stroke = 92 x 86 mm.
- Received permission to publish the data and results from authors.



Meshing

- Two different methods for meshing.
  1. Using commercial software: GridPro (top figure).
  2. Using open-source software: *snappyHexMesh* (bottom figure).
- Challenges in Meshing
  1. Valve closure.
  2. Mesh motion.
  3. Mesh to Mesh mapping and mesh quality due to deformation.



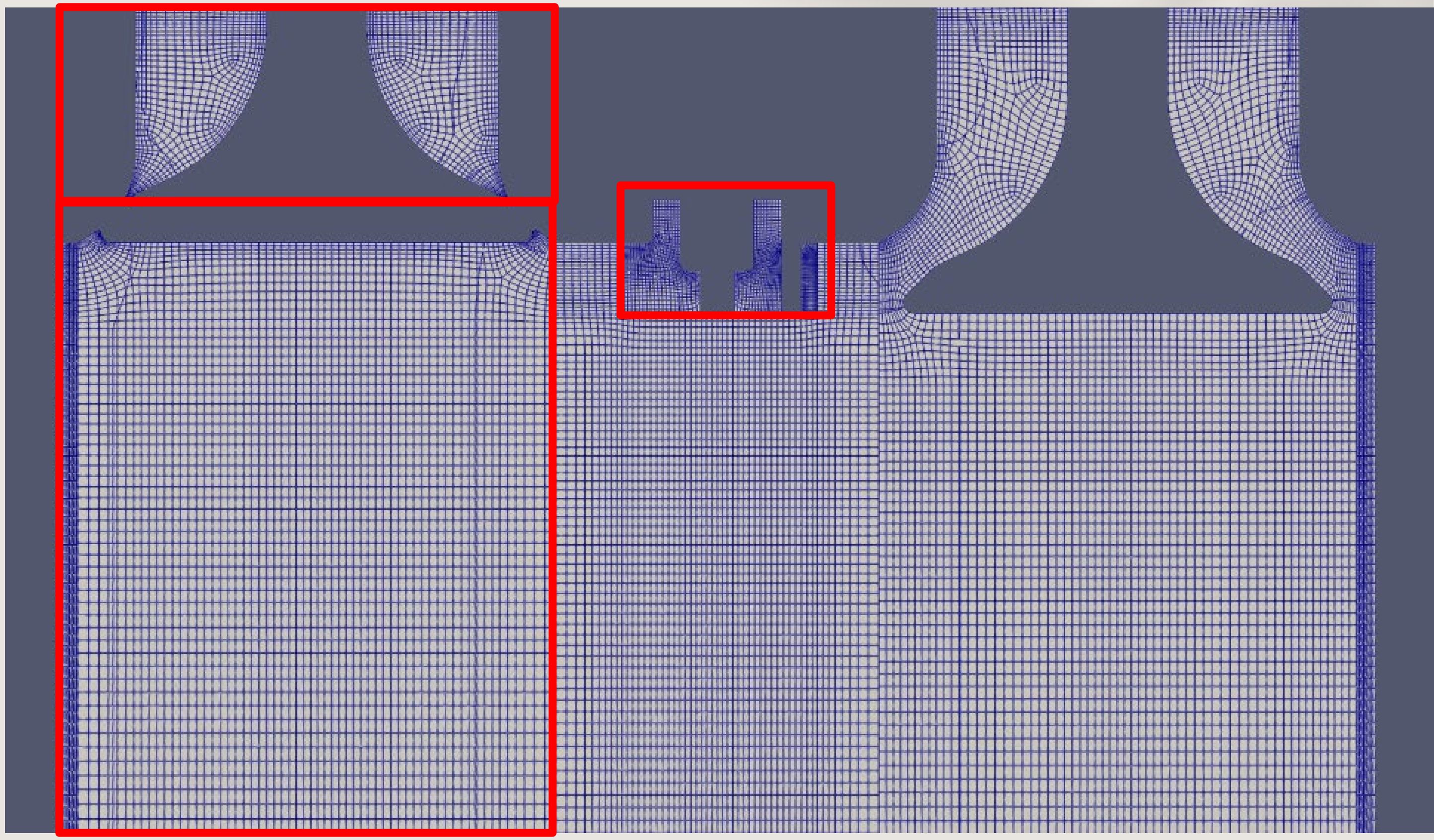


Meshing Challenges and Solutions

Challenges	Solution	Availability
Mesh Motion	AATE – Mesh mover	Publicly Available
Complex Geometry	Mesh modularity: NCC	Publicly Available.
Mesh deformation	Mesh to Mesh mapping	Publicly Available

Grid Pro : Valve closure

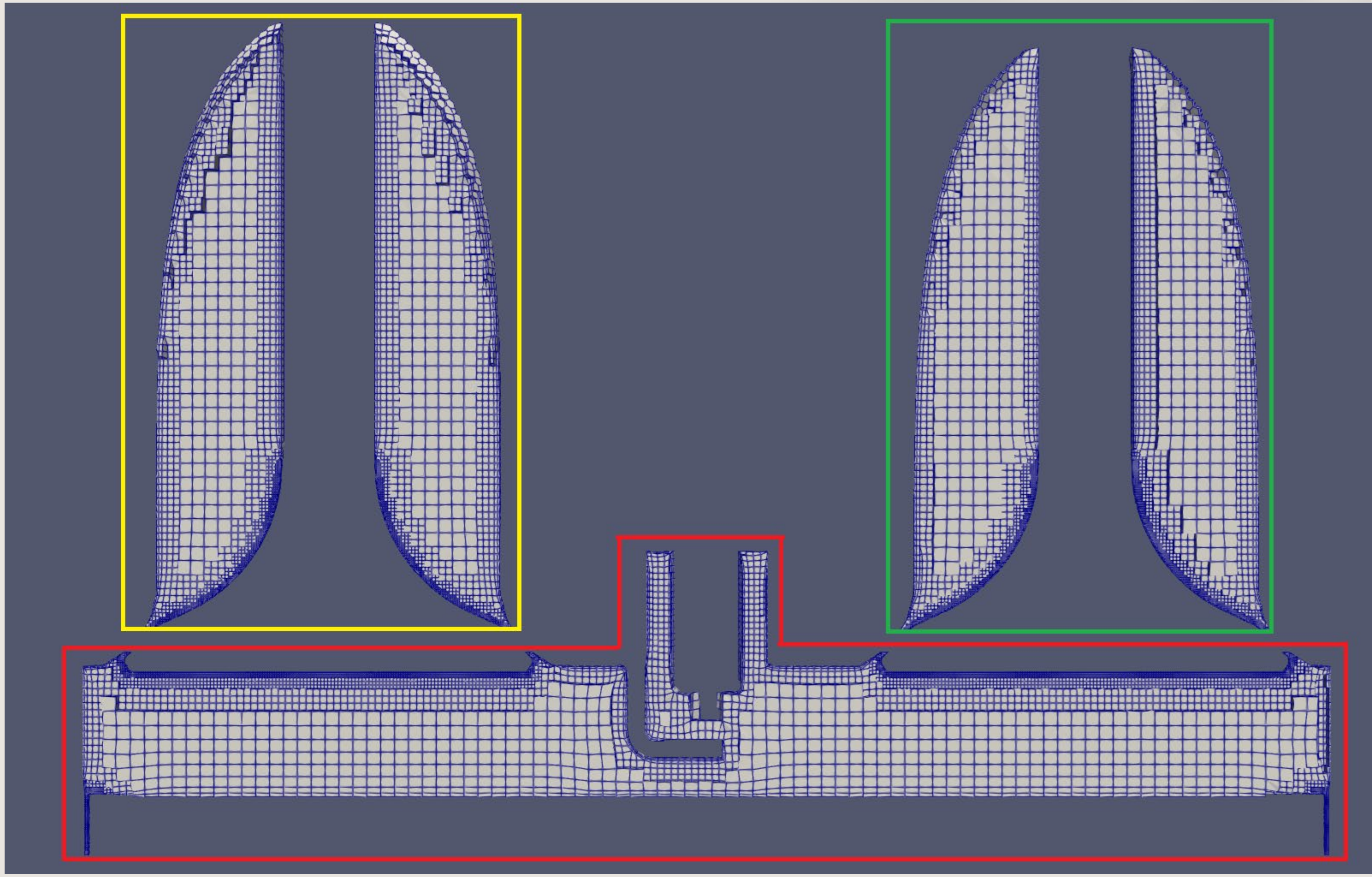
- ~3 million cells BDC, 0.4mm base size.
- Minimum gap: 0.1 mm
- Separate mesh was generated for different patches.
- The two-mesh body interacts with Non-conformal coupling (NCC).



Mesh generated using GridPro

snappyHexMesh: Valve closure

- ~3.5 million cells at BDC, 1 mm base size.
- Minimum gap : 0.45 mm
- Closed valves (intake valve- within green box) (exhaust valve yellow box) meshed separately than rest of the geometry (red box) and merged together.

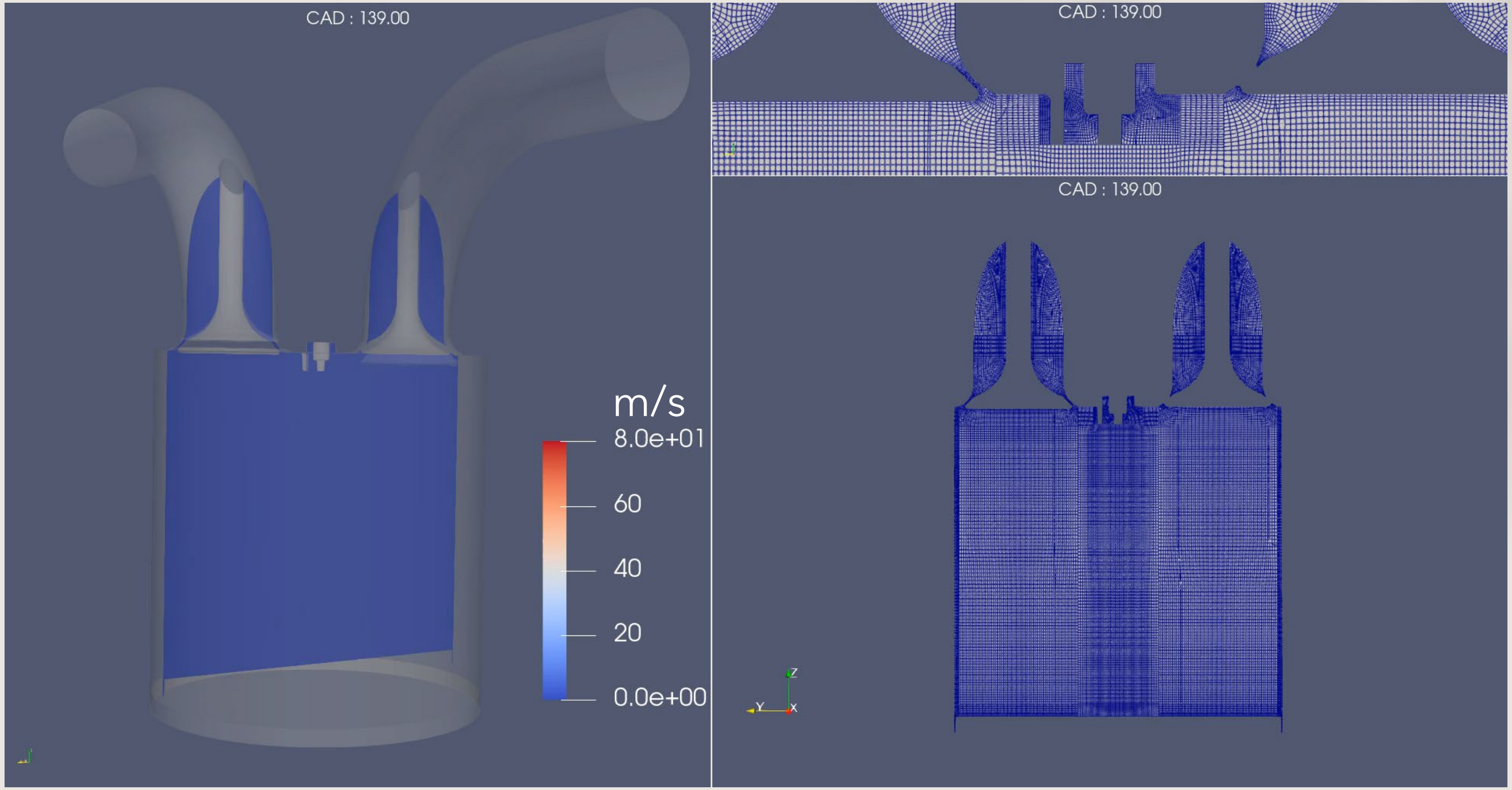


Model Setup

Turbulence modelling:	k-omega SST (RANS)
Advective fluxes:	limitedLinear
Wall modelling:	wall functions
Pressure-velocity coupling:	PIMPLE
Time stepping:	Variable based on CFL criterion

Meshing: Mesh motion and Mapping

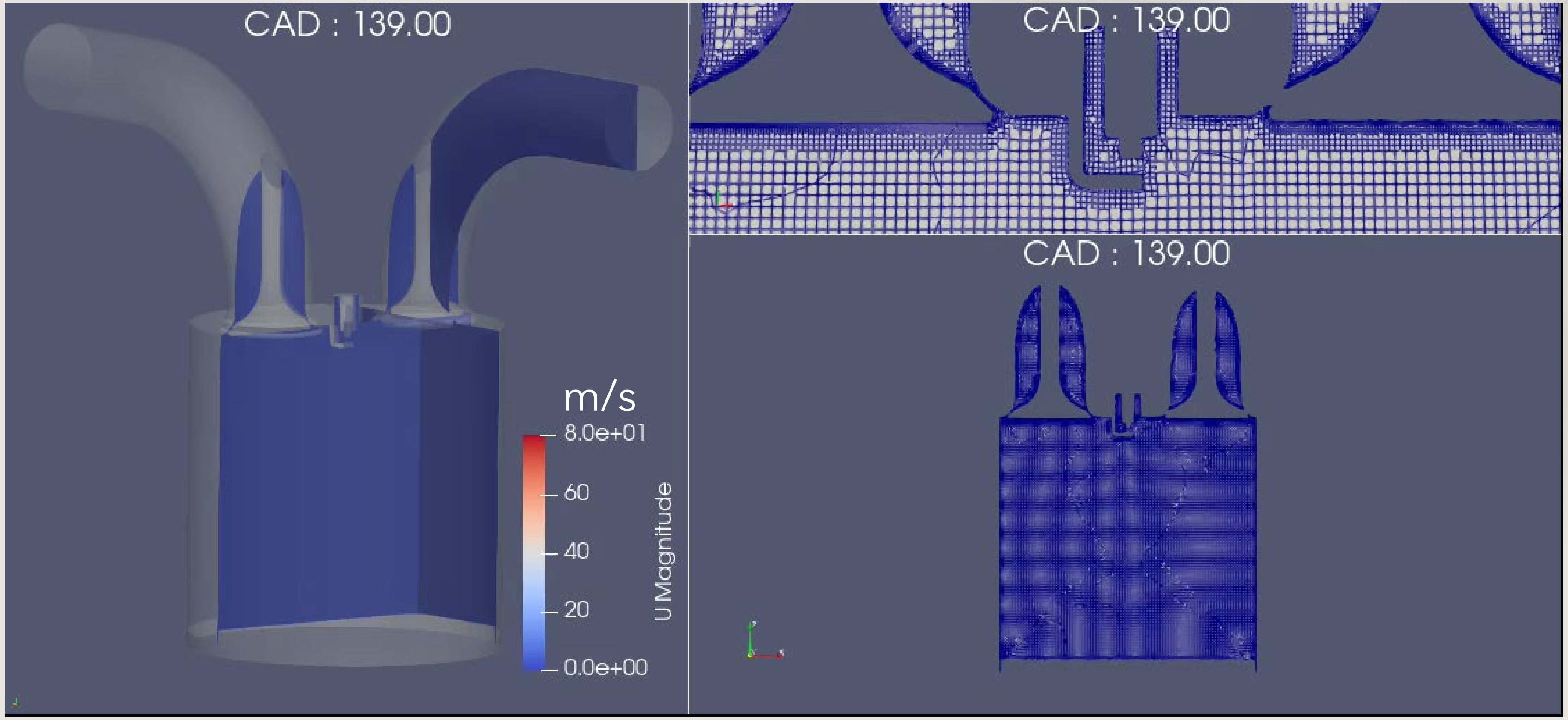
- Mesh Mover
  - Wärtsilä in-house built mesh mover.
  - Released under OpenFOAM-dev.
  - Mesh quality was monitored frequently throughout the simulation.



Simulation including Mesh motion and mapping for TCC-iii engine using using GridPro mesh.

Meshing: Mesh motion and Mapping

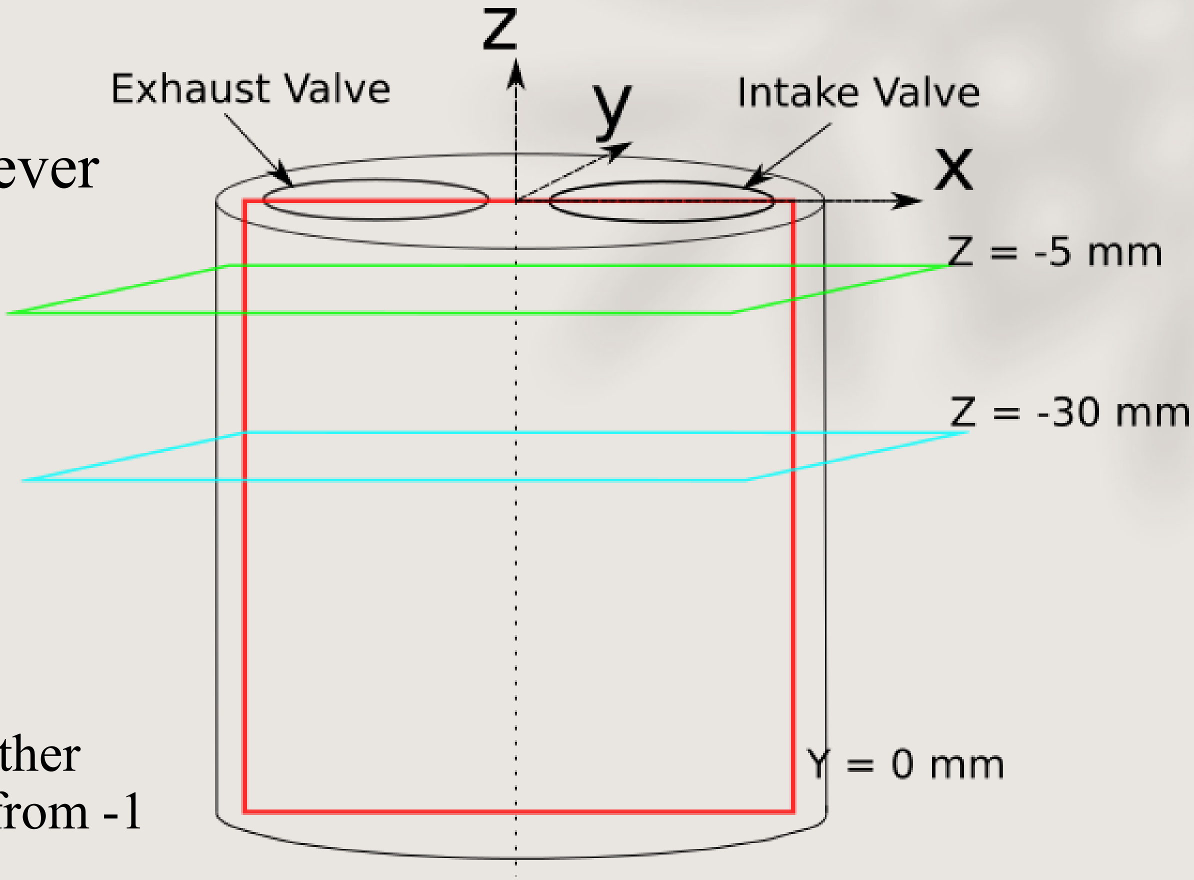
- Mesh Mapping
  - OpenFOAM's mesh mapping algorithm.
  - Snappy Mesh requires more instances, as the mesh deforms significantly than GridPro mesh.



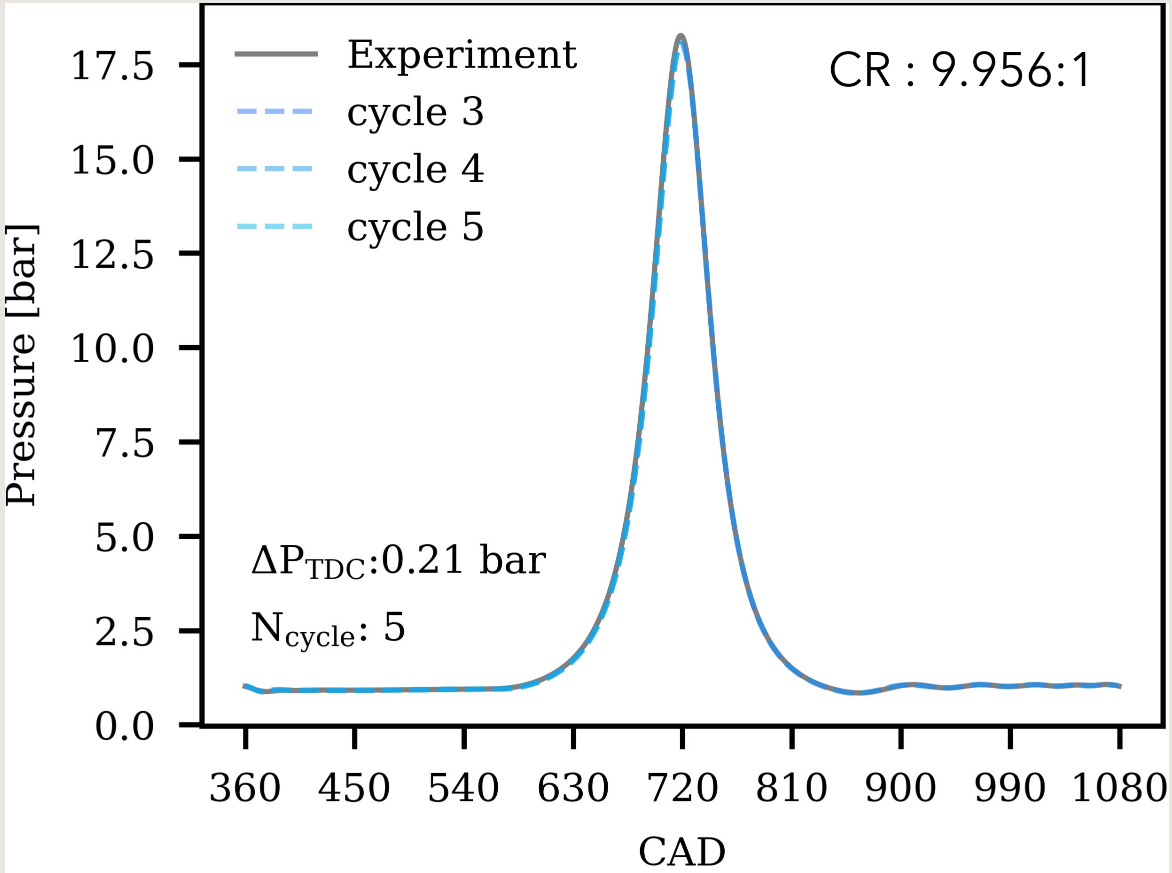
Simulation including Mesh motion and mapping for TCC-III engine using Snappy Hex mesh.

Validation

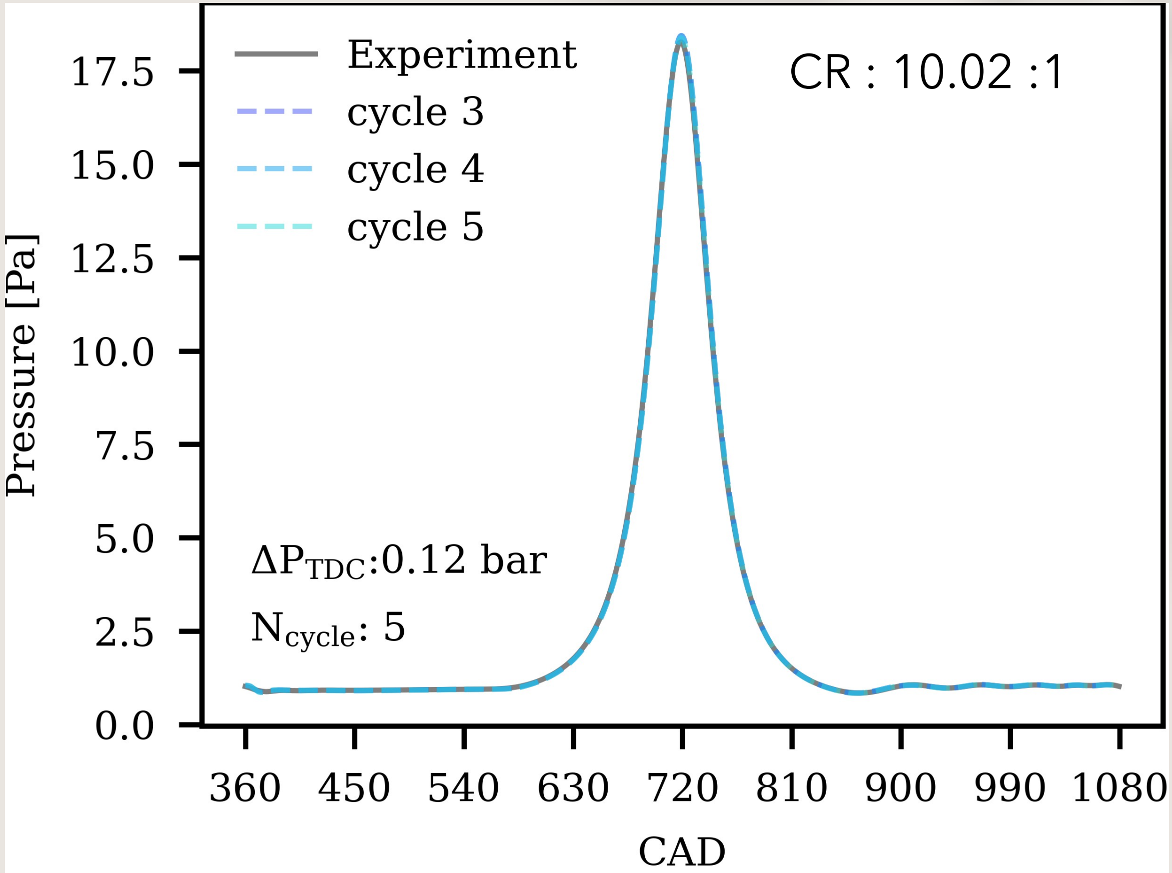
- Validation was done with extensive experimental PIV data available in TCC engine repository of University of Michigan.
- Simulation was done for 5 (0 to 5) cycles, however 0, 1 and 2 cycle was omitted from calculation.
- Compression Ratio (CR).
- Pressure inside the cylinder.
- Phase averaged velocity.
- Comparative Indices: compares results between experimental and simulated flow fields.
  - **Relevance Index (RI):** It projects one vector to another vector. It shows the orientation of the vector. Value from -1 to 1.
  - **Magnitude Index (MI):** It considers both orientation and magnitude of vector. Values from 0 to 1.



Post processing: Motored pressure

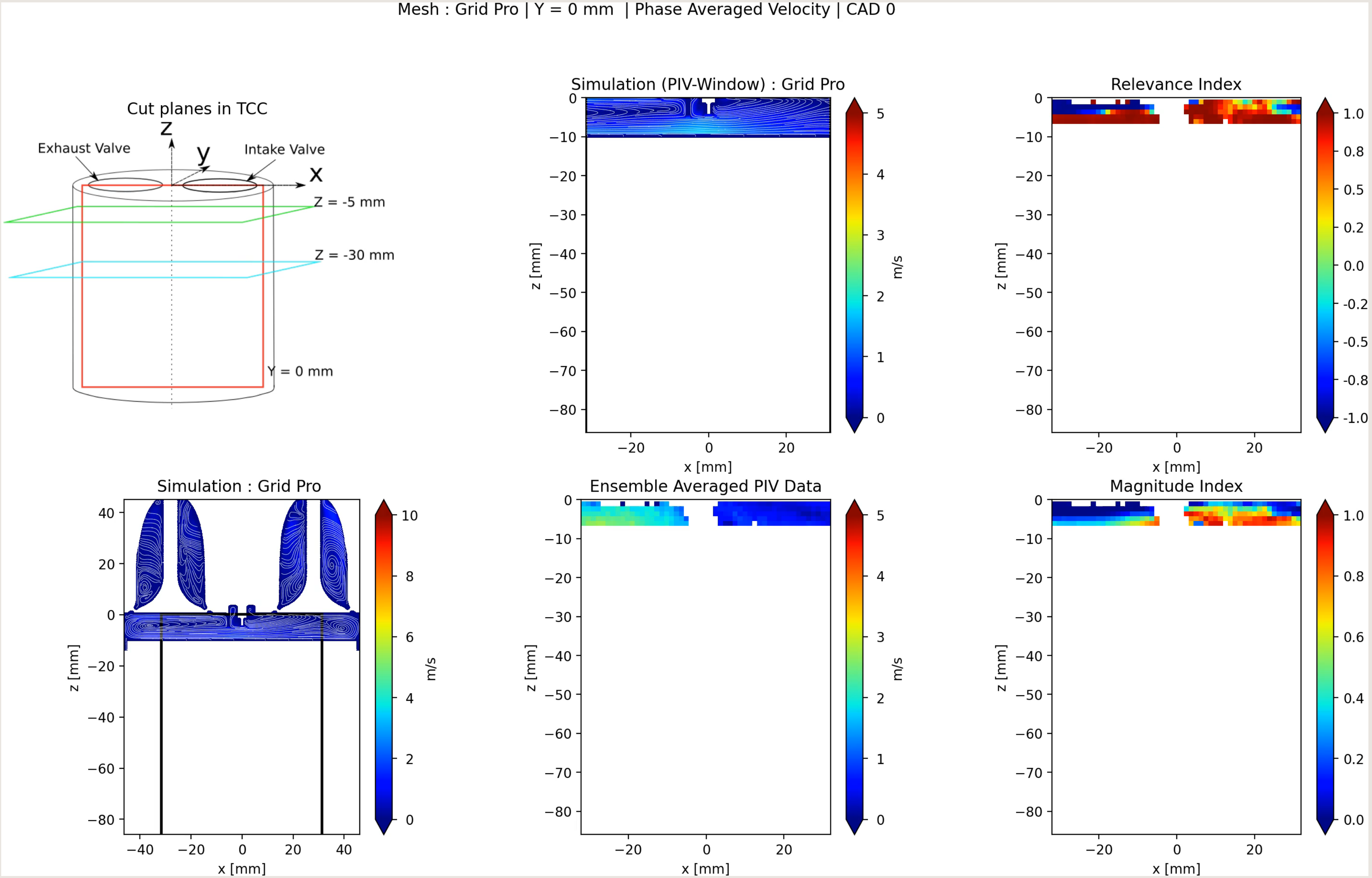


Motored pressure curve for TCC-III engine from GridPro Mesh.



Motored pressure curve for TCC-III engine from snappyHexMesh.

Phase-averaged velocity data: Y = 0 mm (GridPro)



Relevance Index (RI): -1 to 1 compare direction

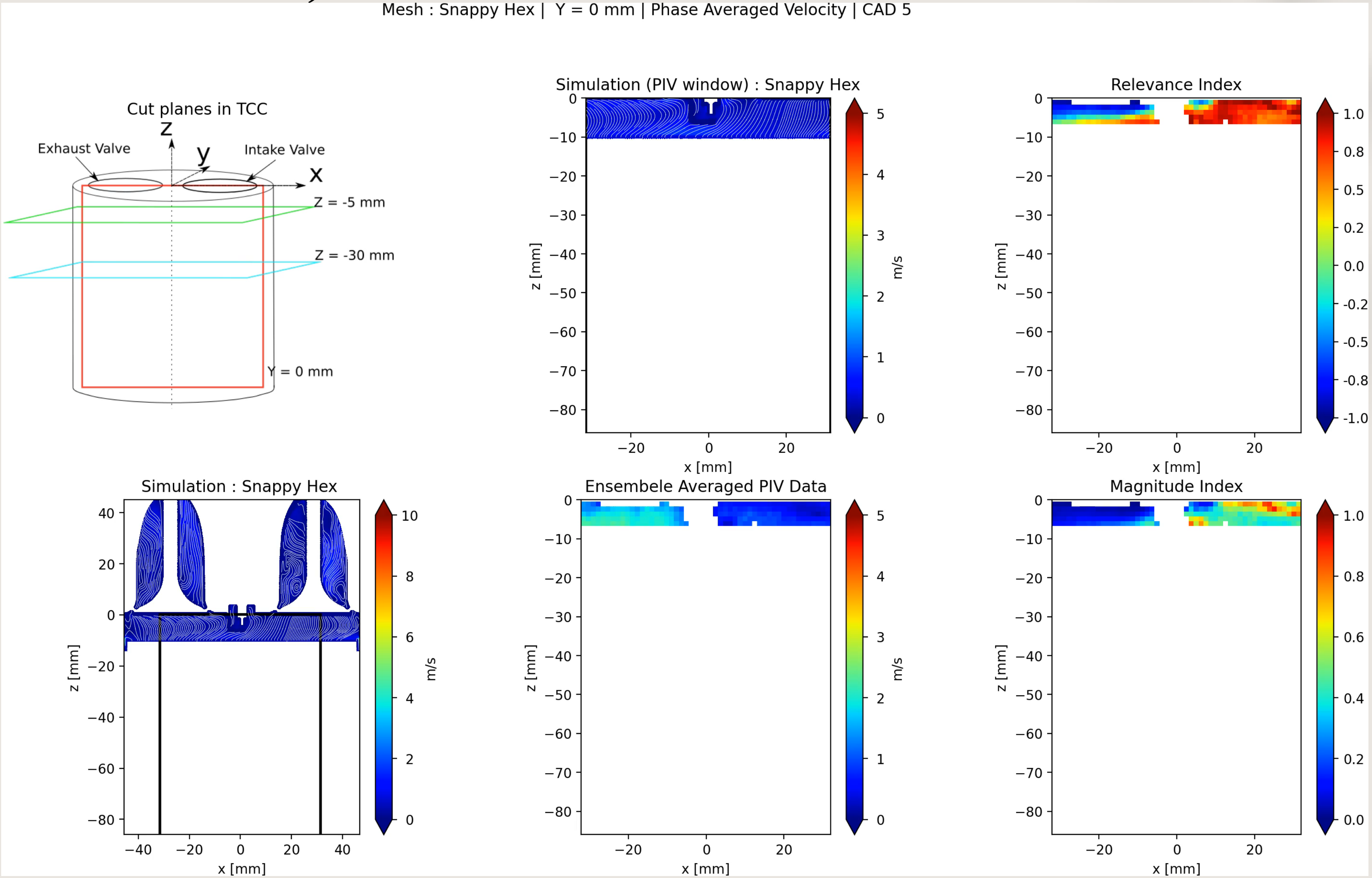
$$RI = \frac{< u_{sim} >. < u_{piv} >}{||u_{sim}||. ||u_{piv}||}$$

Magnitude Index(MI): 0 to 1, compares direction and magnitude.

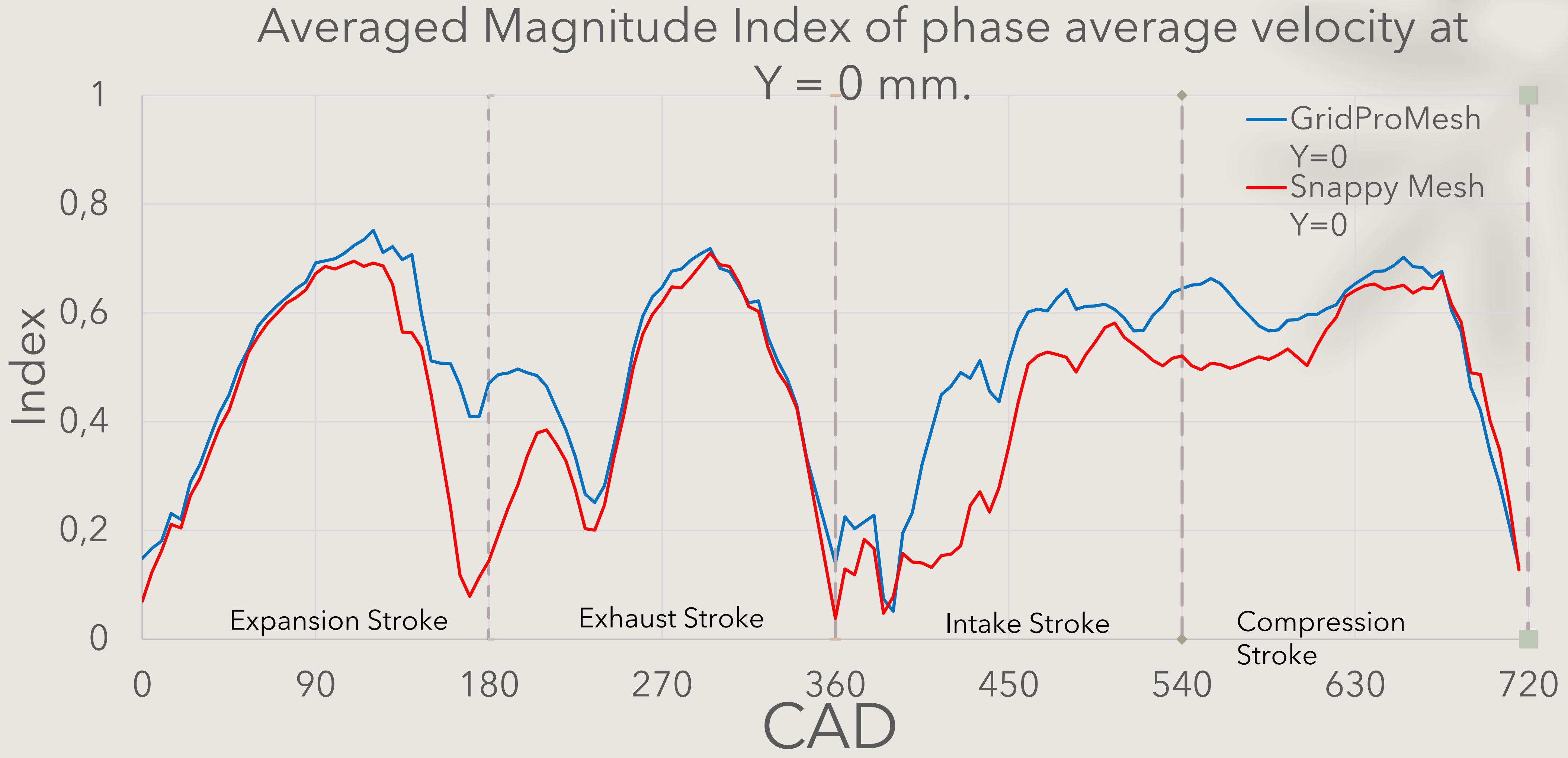
$$MI = 1 - \frac{|| < u_{sim} > - < u_{piv} > ||}{||< u_{sim}>|| + ||< u_{piv}>||}$$

<>, denotes phase-avg velocity data, || denotes magnitude of the vector.

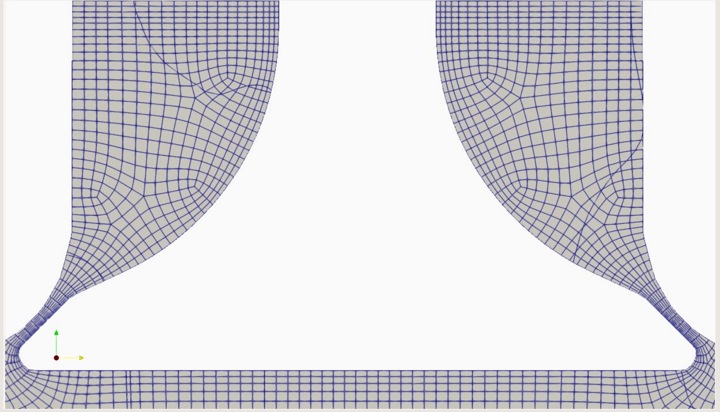
Phase-averaged velocity data : Y = 0 mm (snappyHexMesh)

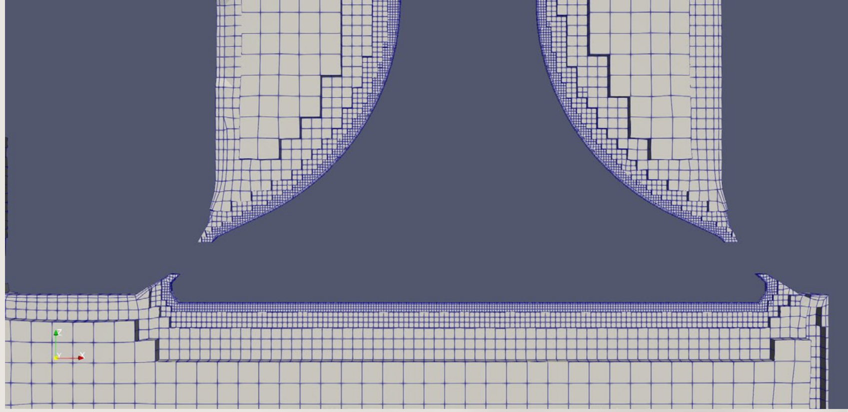


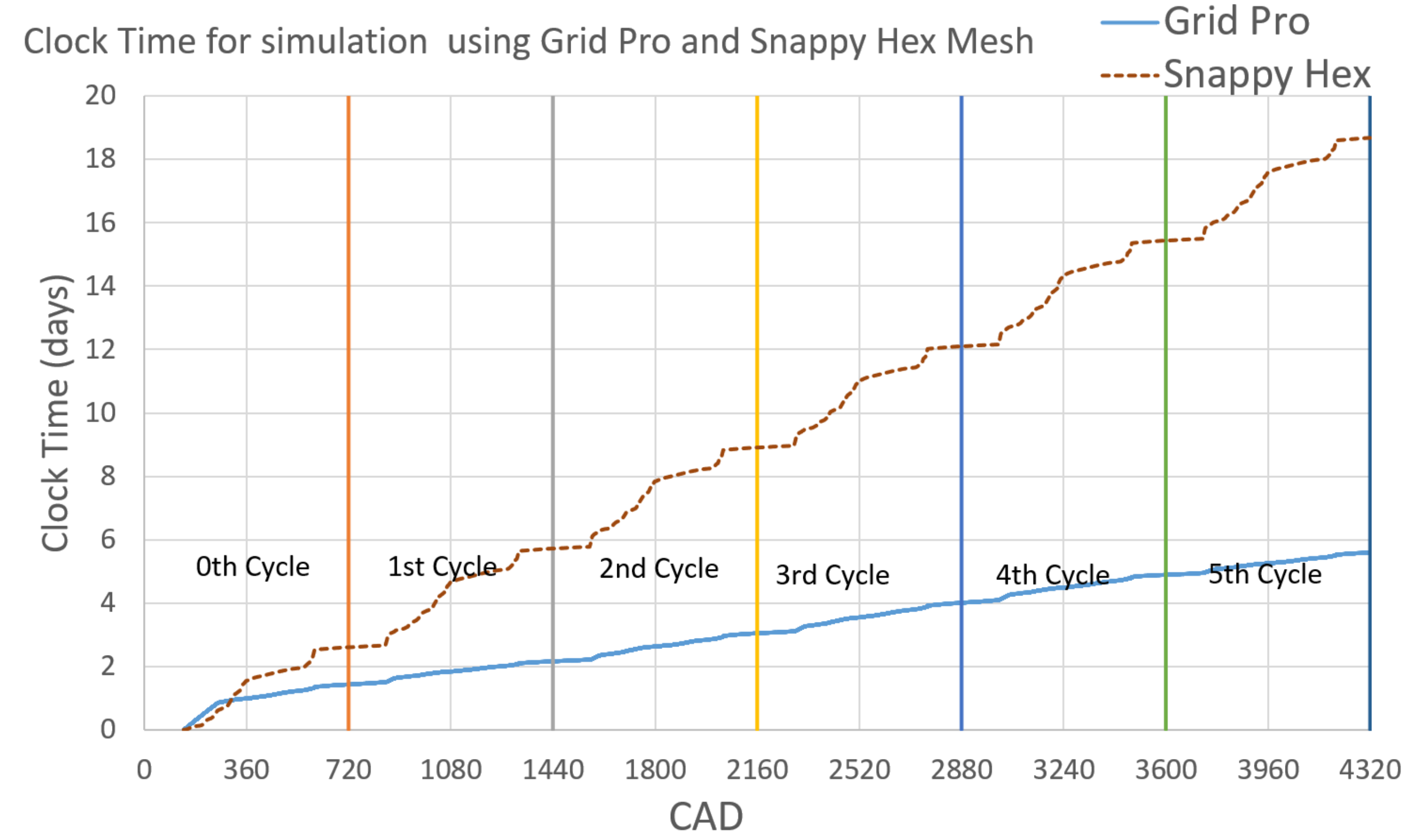
Average Magnitude Index Y = 0 mm [0 to 1]

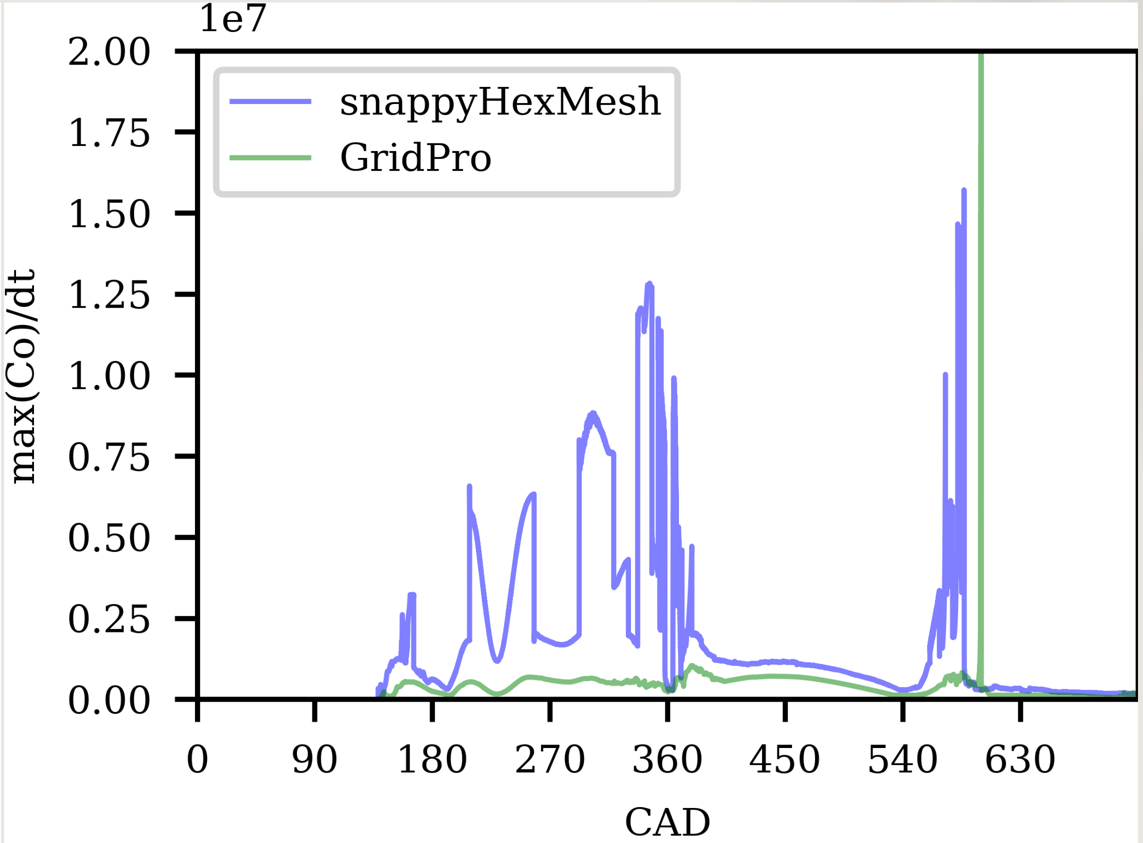


Simulation time









** GridPro simulation was run on Aalto computing resource (Triton), whereas snappyHex Mesh was run on wärtsilä cluster (StarGate).

** GridPro has much strict time stepping limitation, maxDeltaT. of 0.05 CAD, whereas for snappy Hex Mesh it was 0.2 CAD.

Conclusion

- A CFD benchmarking model for IC engine model has been created with commercial and open-source meshing solution.
- The model has been validated with experimental flow field data and results from both meshing solution, snappy hex mesh and GridPro is in good agreement with the experimental PIV data.
- Due to body conformed mesh generation ability of GridPro, the results during valve opening and closing is better in GridPro.
    - To capture small gaps in the geometry, snappy hex mesh requires small cells. This will increase the simulation time.
- This model will made available for all users to use and modify.

For a video summary and link to the report

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