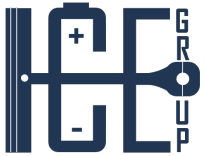


POLITECNICO
MILANO 1863

6th Two-Day Meeting on Propulsion Simulations Using OpenFOAM Technology

Full cycle IC Engine simulation methodology with flexible automatic mesh generation

Giovanni Gianetti
Internal Combustion Engine Group, Politecnico di Milano, Department of Energy

Acknowledgments

- Gianluca D’Errico
- Tommaso Lucchini
- Lorenzo Sforza
- Federico Ramognino
- Alessandro Nodi

Topics

1. **Background: future of IC engines**

2. **Full-cycle mesh generation**
   - Multiple meshes approach
   - Methodology validation

3. **Closed-valves mesh generation**
   - Dynamic layering approach
   - Methodology validation

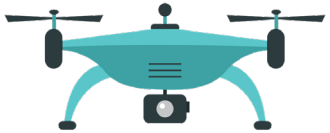
4. **Conclusions**

Future of IC Engines

- Efficiency increase
- Reduction of emissions
- New applications

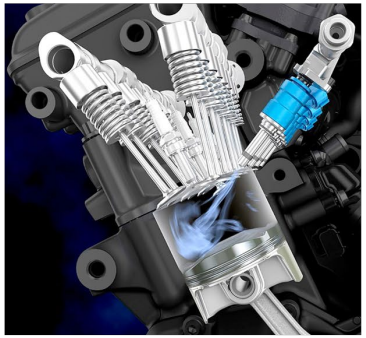




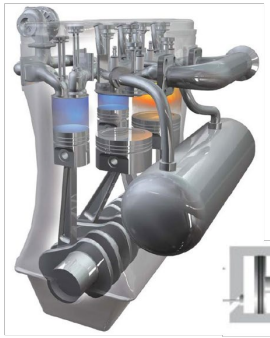
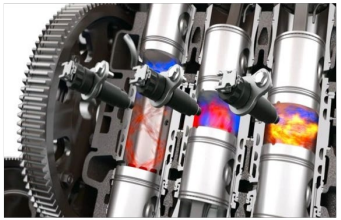
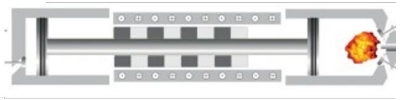



Hydrogen engines

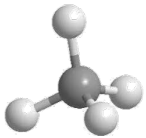


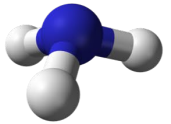
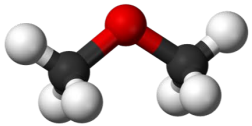
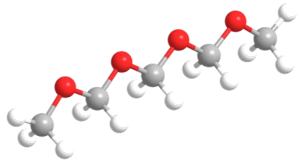


New engine concepts

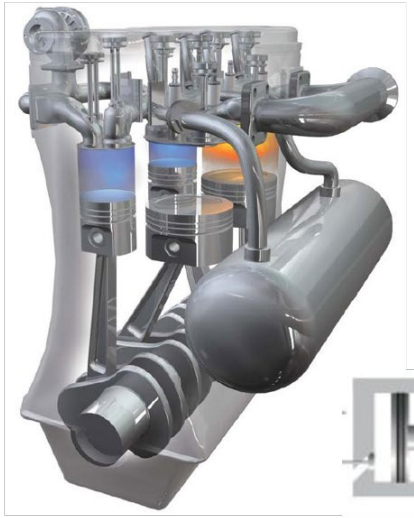




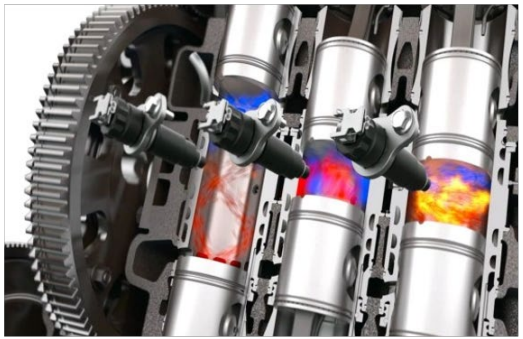
Alternative fuels

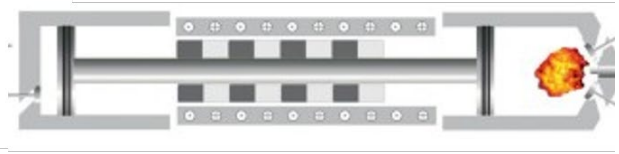


New engine concepts





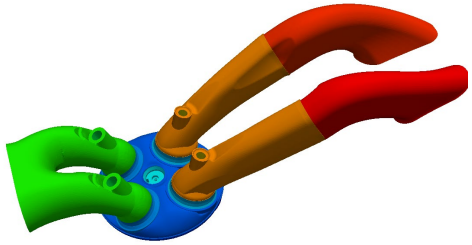


- New challenges for meshing procedure

Flexible approach able to be applied for different type of engines configurations

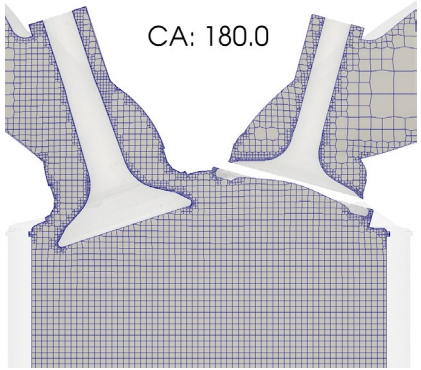
Lib-ICE : mesh management

Full-cycle simulation

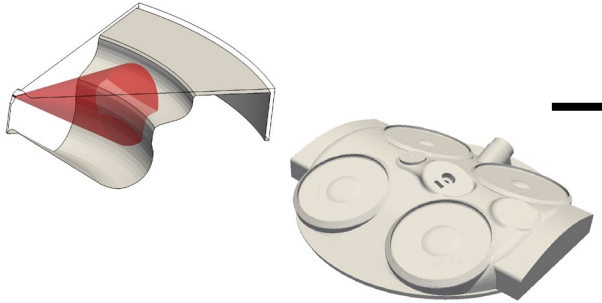


LibICE
OpenFOAM

Multiple meshes approach

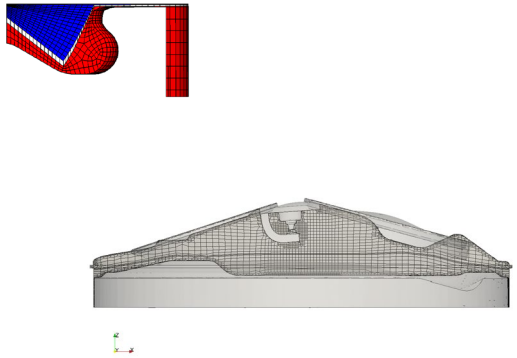


Power-cycle simulation



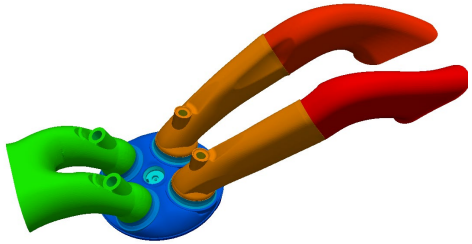
LibICE
OpenFOAM

Dynamic-layering



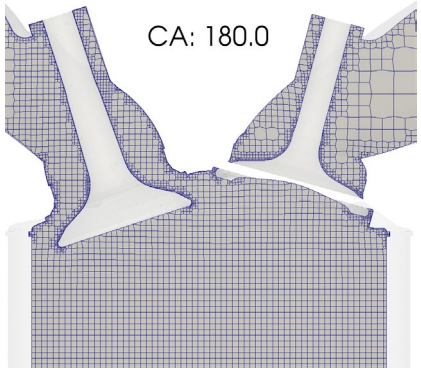
Lib-ICE : mesh management

Full-cycle simulation

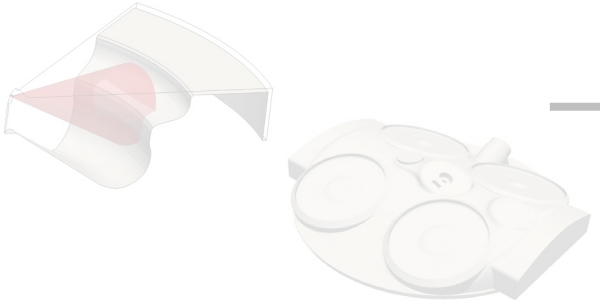


LibICE OpenFOAM

Multiple meshes approach



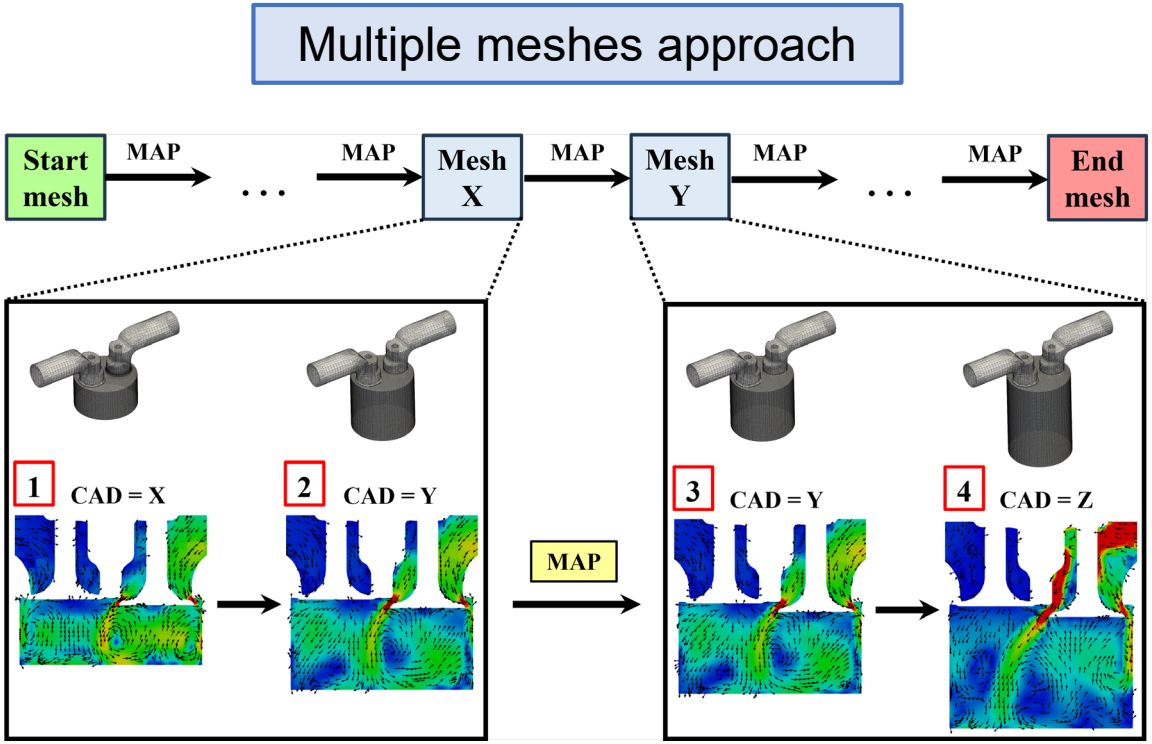
Power-cycle simulation



LibICE OpenFOAM

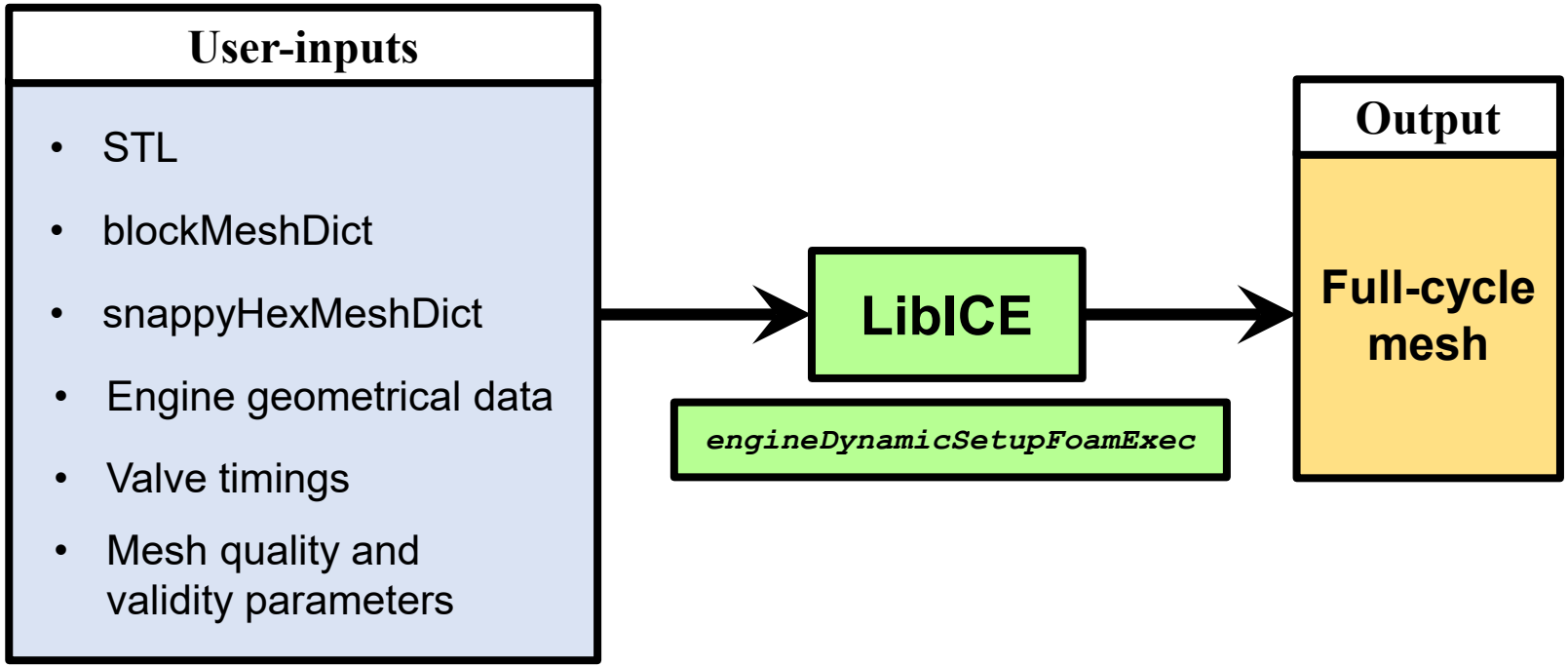
Dynamic-layering

Full cycle simulation – multiple meshes approach



1) **Multiple meshes** cover the entire cycle simulation.
2) Each mesh is valid in a user-specified interval.
3) **Automatic mesh generation** from surface file of the combustion chamber.
4) During each time-step:
   - ✓ Grid points are moved using automatic mesh motion and/or pre-defined points motion.
   - ✓ Mesh topology can be eventually changed
5) Mesh-to-mesh interpolation.

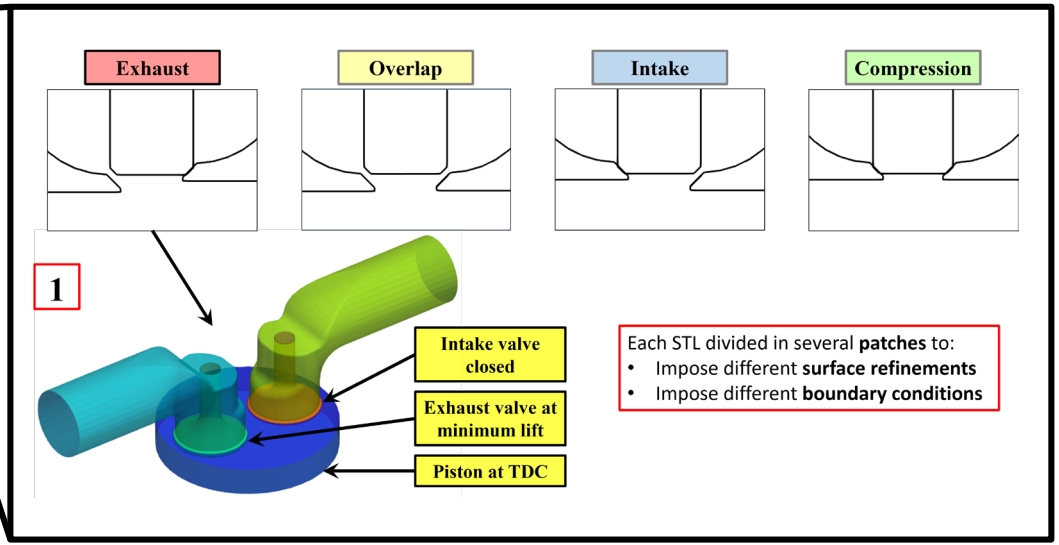
User-inputs for mesh generation



User-inputs for mesh generation

User-inputs

- STL
- blockMeshDict
- snappyHexMeshDict
- Engine geometrical data
- Valve timings
- Mesh quality and validity parameters



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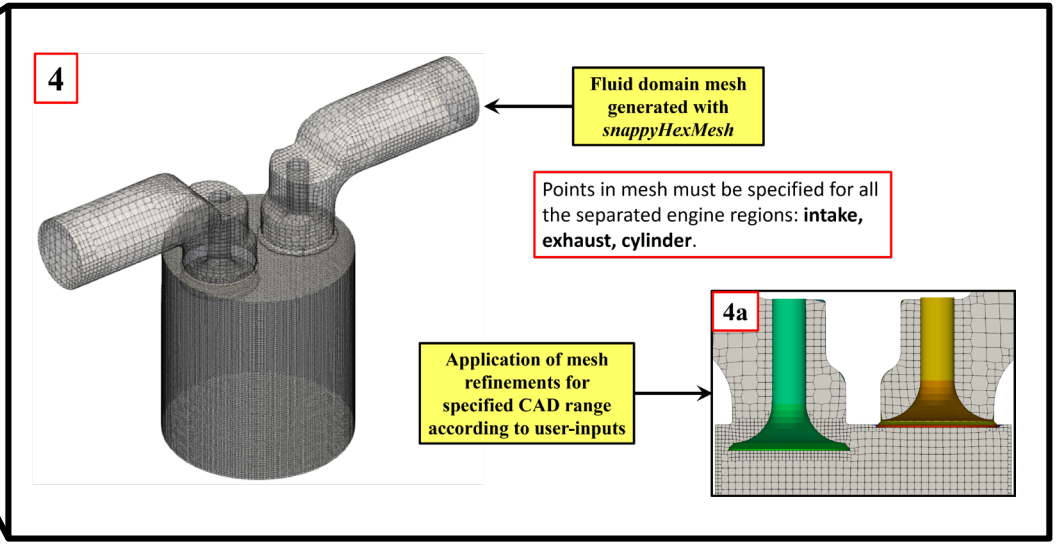
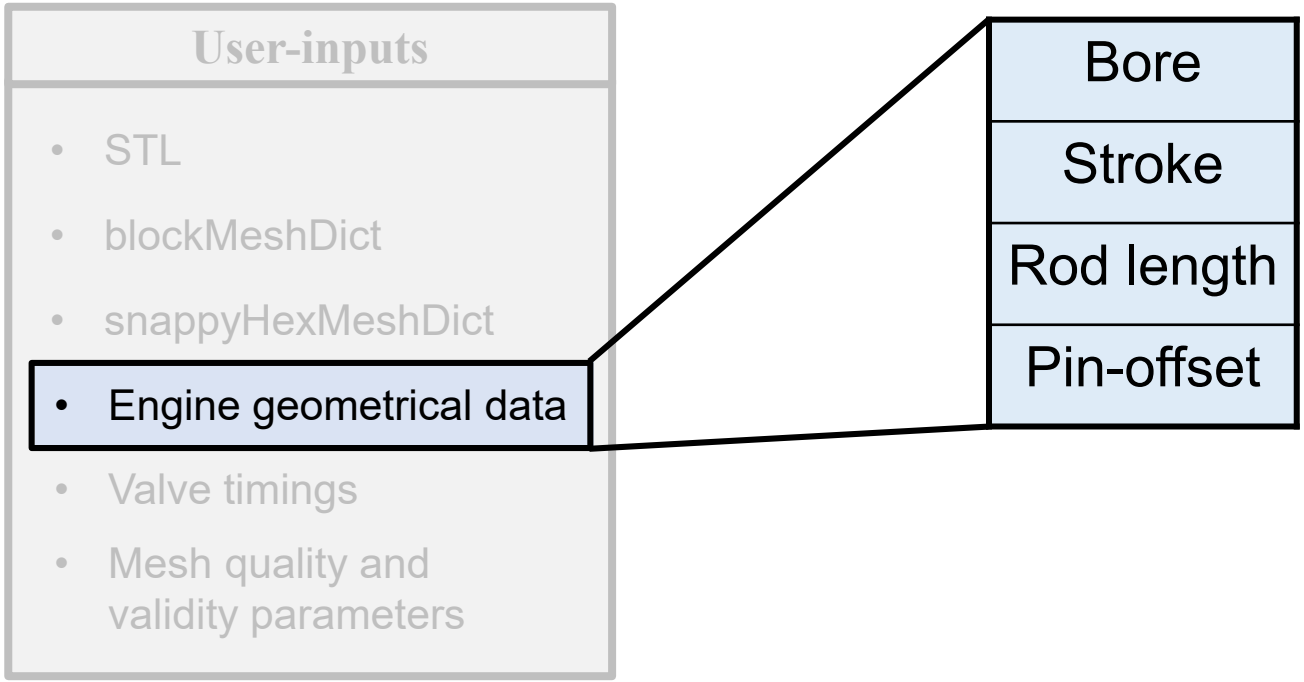


User-inputs for mesh generation

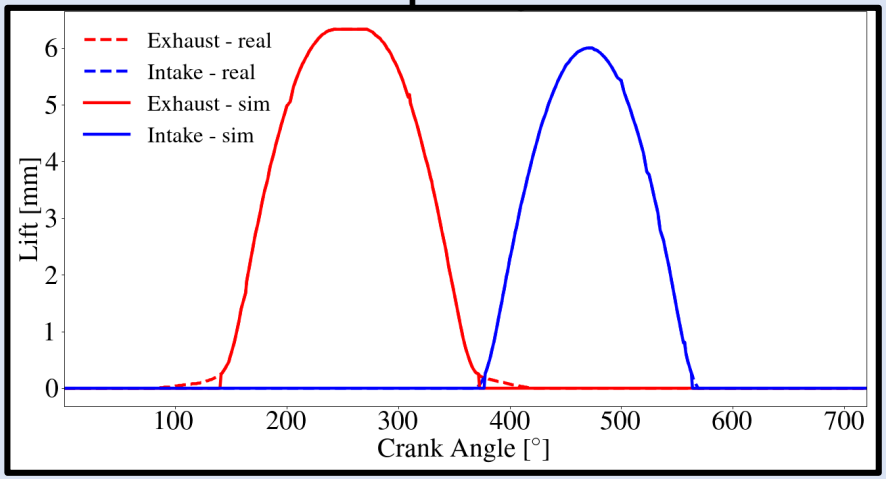


User-inputs for mesh generation

User-inputs

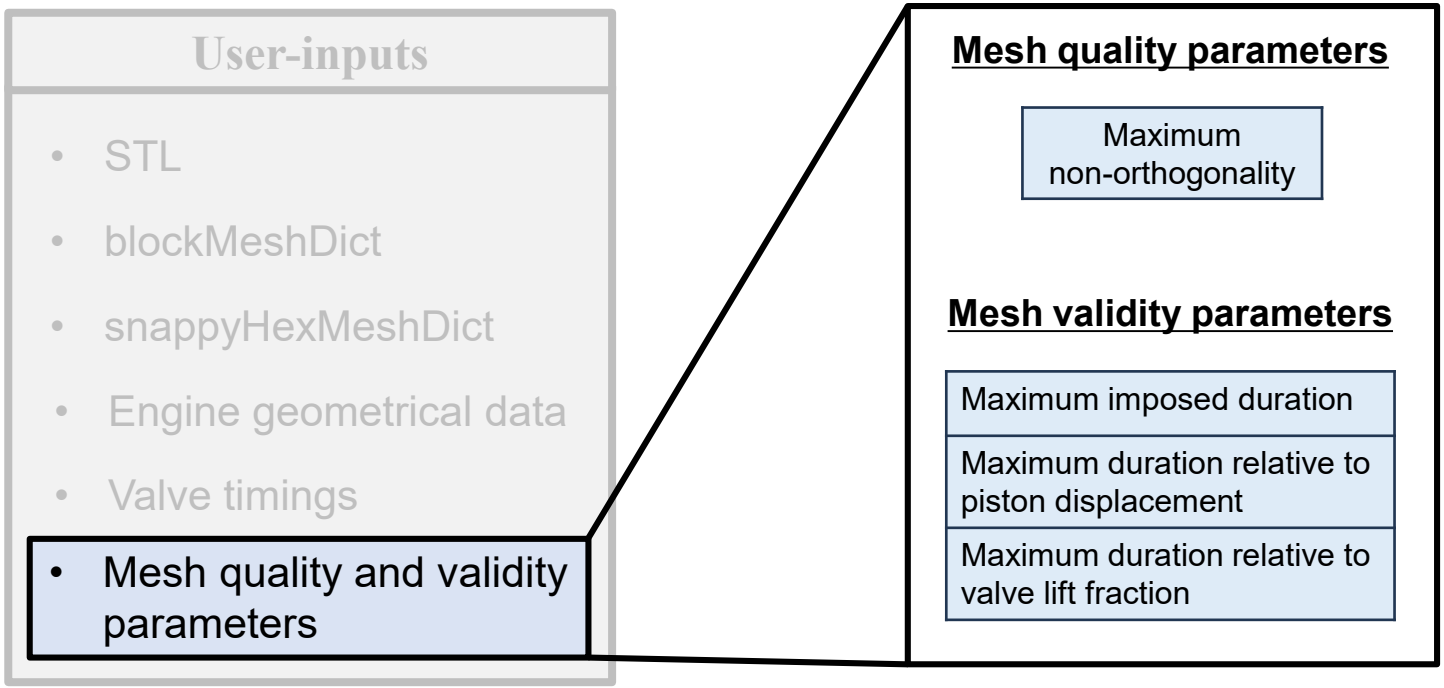
- STL
- blockMeshDict
- snappyHexMeshDict
- Engine geometrical data
- **Valve timings**
- Mesh quality and validity parameters

Lift profiles

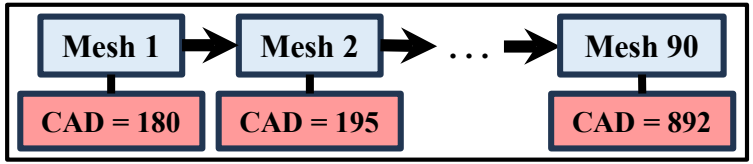


Minimum valve lift: trade off between simulation accuracy and computational time

User-inputs for mesh generation



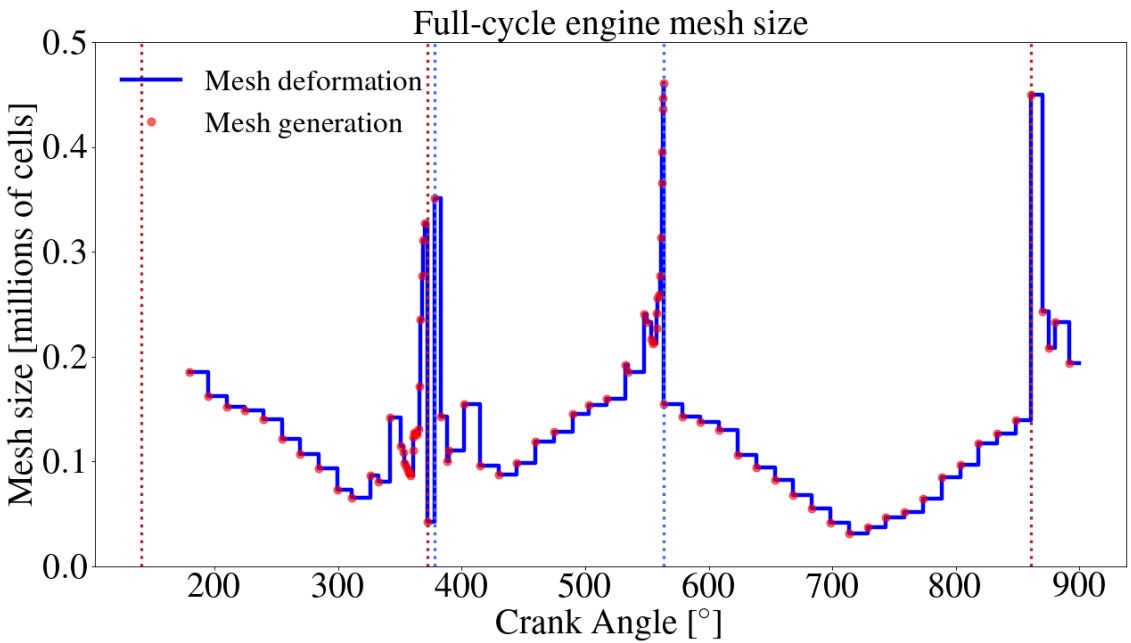
Full-cycle mesh motion



In this example, the engine full-cycle is covered with 90 meshes

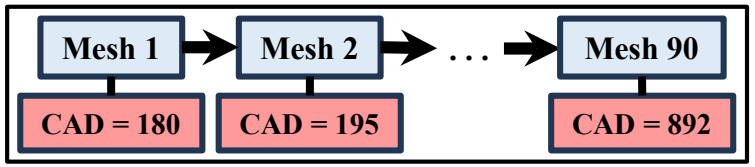
The mesh number of cells varies depending on:

- The cylinder volume variation
- The activation/deactivation of mesh refinements for specified CAD ranges

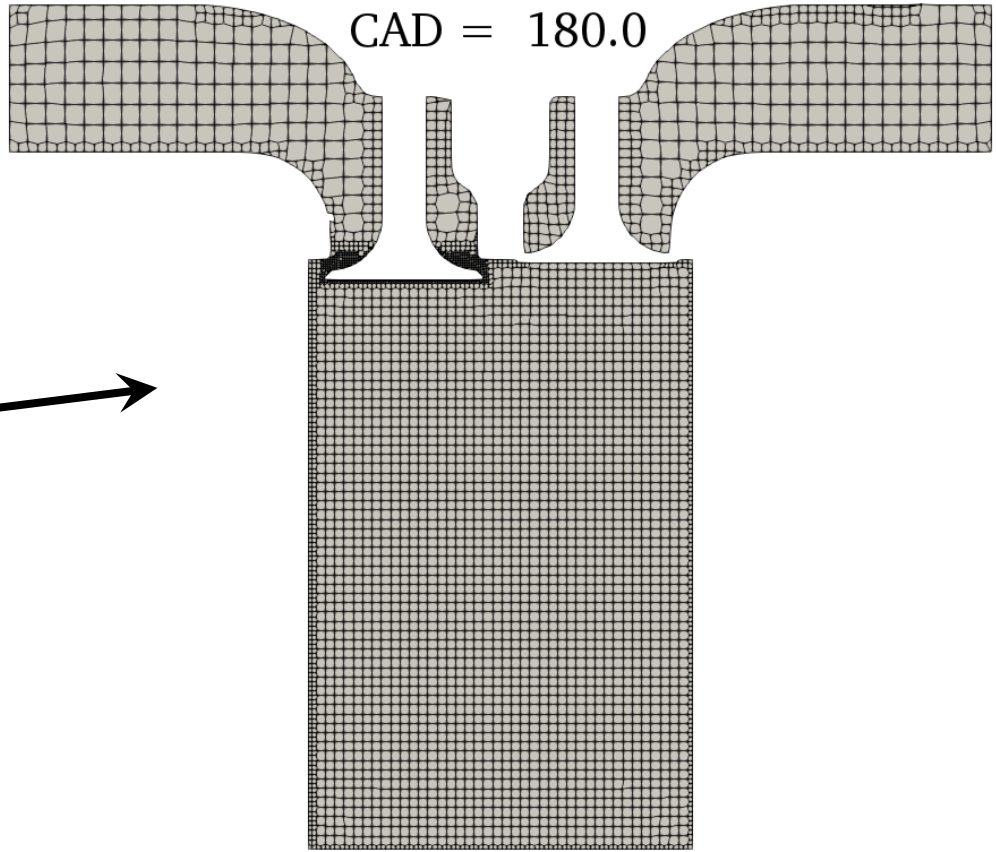


	EVO	EVC	IVO	IVC
CAD [°]	141	372	377.8	563.4

Full-cycle mesh motion



The result of the sequential concatenation of all the created dynamic mesh is the engine full-cycle motion



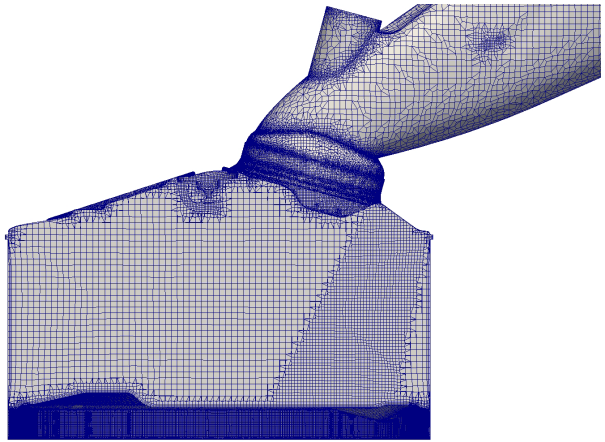
The CFD simulation will be carried out by means of a **multi-mesh approach**.

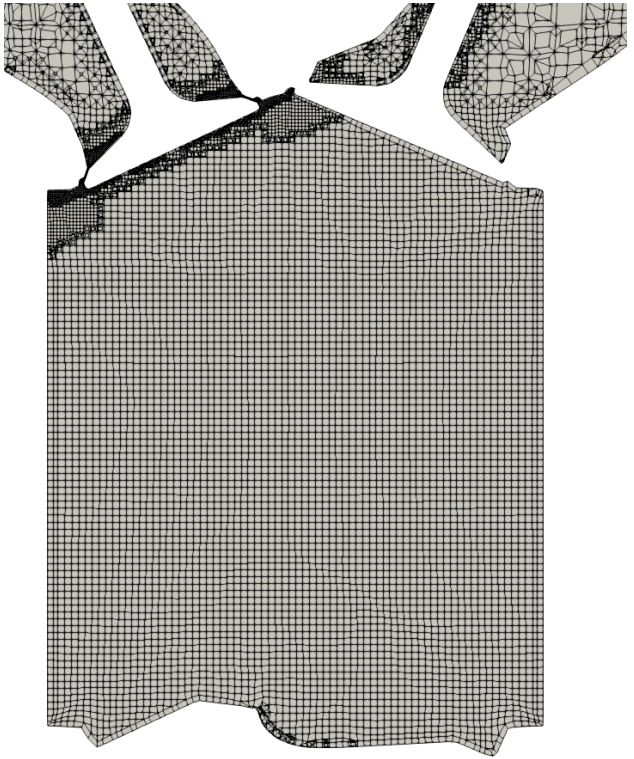
Full-cycle mesh simulations

Flexible approach, **tested on more than 40 geometries** in the context of industrial/public projects, PhD/MSc theses:

- 4S-SI + tumble
- 4S-SI/CI + swirl
- 2S uniflow / crossflow

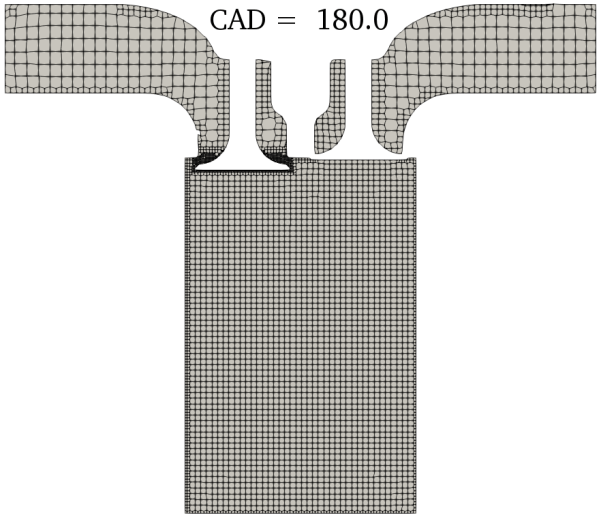
Possibility to include «floating» refinements (FMR) to better describe relevant flow features and fuel-air mixing





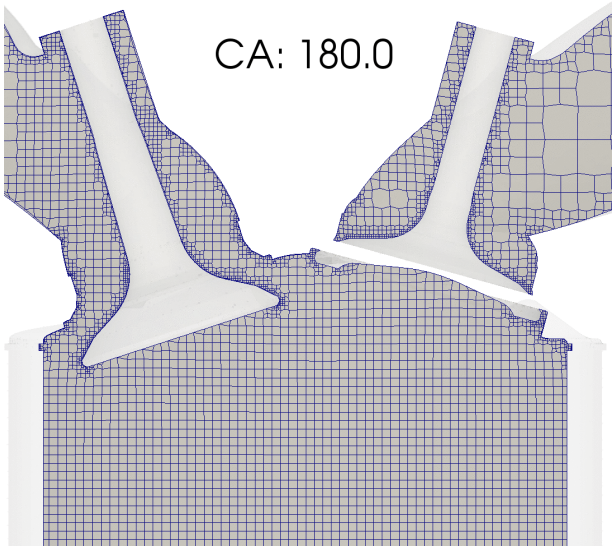
Full-cycle mesh generation - examples

CFR Engine



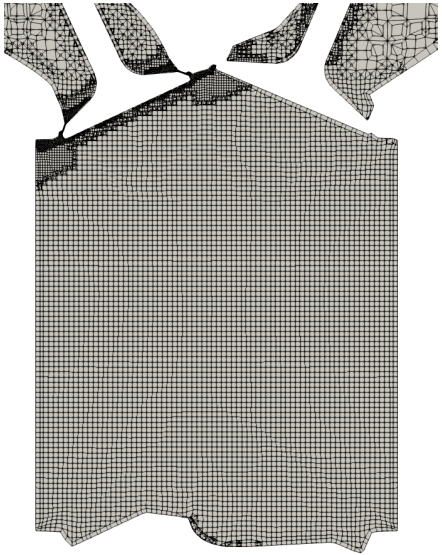
Simple engine with vertical valves and flat piston

SI engine 1



Inclined valves with shaped piston and crevices

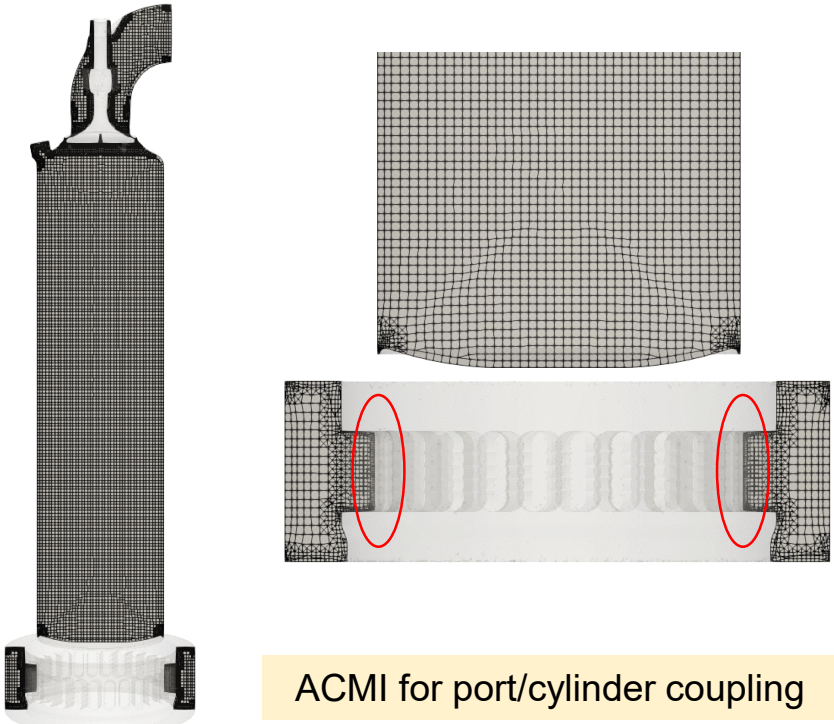
SI engine 2



Application of FMR

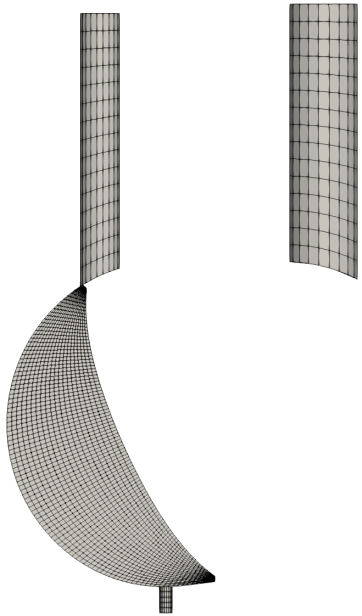
Full-cycle mesh generation - examples

Two-strokes marine engine



ACMI for port/cylinder coupling

Wankel



Particular case: mesh deformation + ACMI

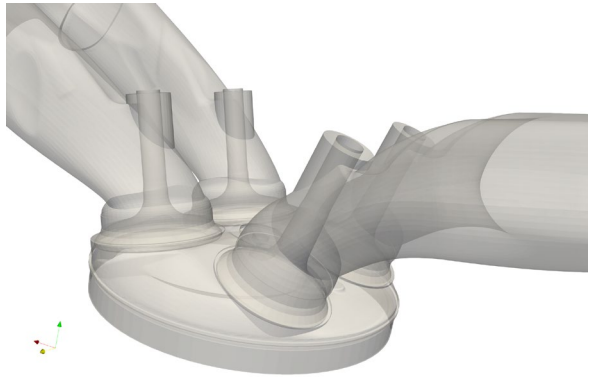
Methodology validation: GDI engine

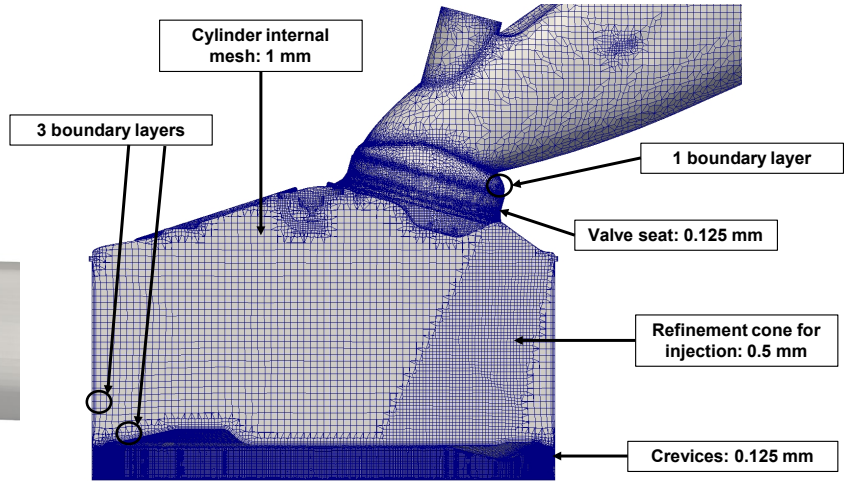
GDI engine

- **3 operating points** investigated
- Each simulations included:
  - **Gas-exchange**
  - **Fuel direct-injection**
  - Combustion

Condition	2000x2	4000x17	5500-Full
Speed [rpm]	2000	4000	5500
BMEP [bar]	2	17	16
ϕ	1	1	1
P injection	50	180	200

Data	Value	U.o.M.
Stroke	85	[mm]
Bore	70	[mm]
Compr. ratio	13:1	[-]
Valves N.	4	[-]

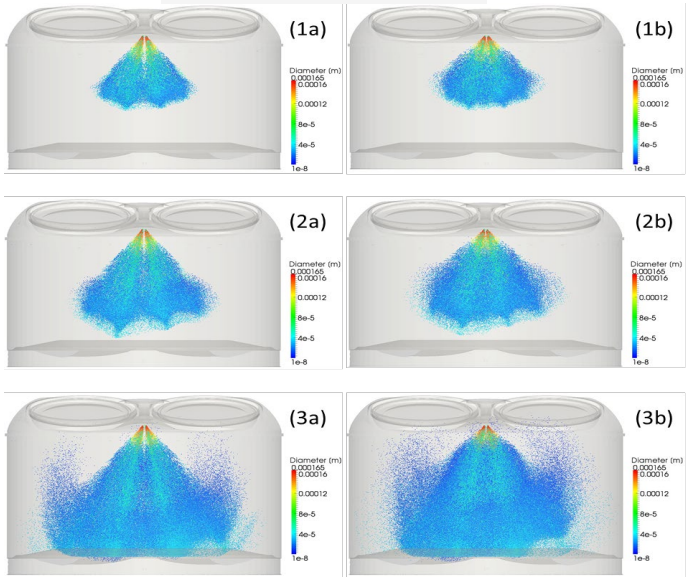




Acknowledgment: ***T. Lucchini***

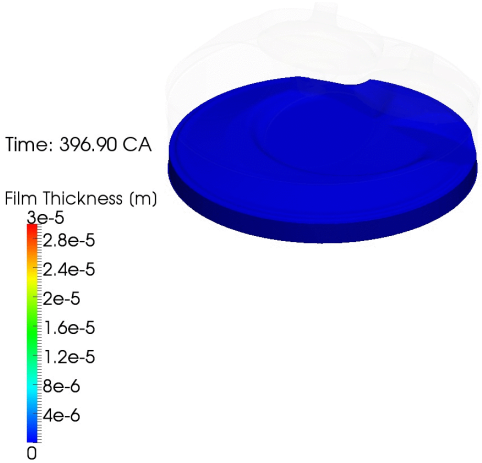
Methodology validation: GDI engine

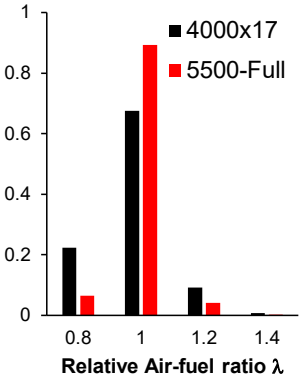
2000x2 – LOW load
Spray evolution



Results

4000x17 and **5500-Full – HIGH loads**
Wall film and mixing





Strong spray collapse due to flash evaporation ⇨ Large spray-angle needed for good mixing

In-cylinder ↑↑ turbulence and ↑↑ charge motion intensity promote air-fuel mixing

Acknowledgment: ***T. Lucchini***

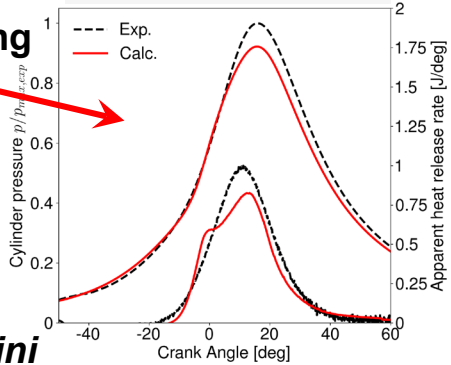
Methodology validation: GDI engine

Results

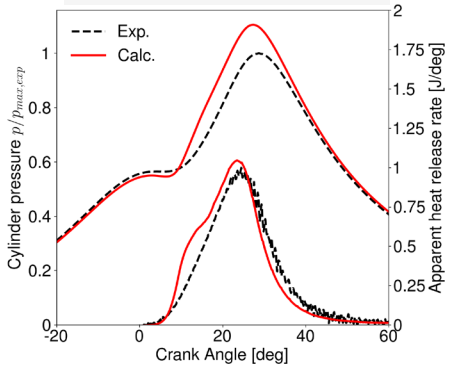
Overall **satisfactory results** achieved at different loads and speeds

- **Low-load is demanding condition** due to:
  - ↓↓ turbulence
  - Stratified charge

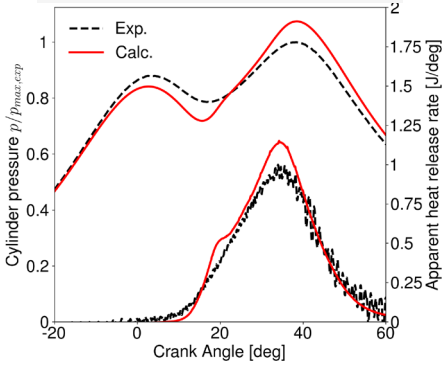
2000x2 – LOW load
Pressure and AHRR



4000x17 – HIGH load
Pressure and AHRR



5500xFull – HIGH load
Pressure and AHRR

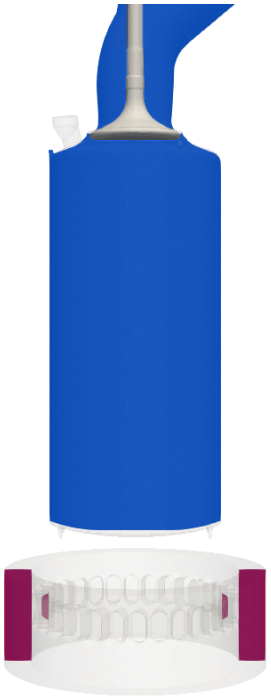


Acknowledgment: ***T. Lucchini***

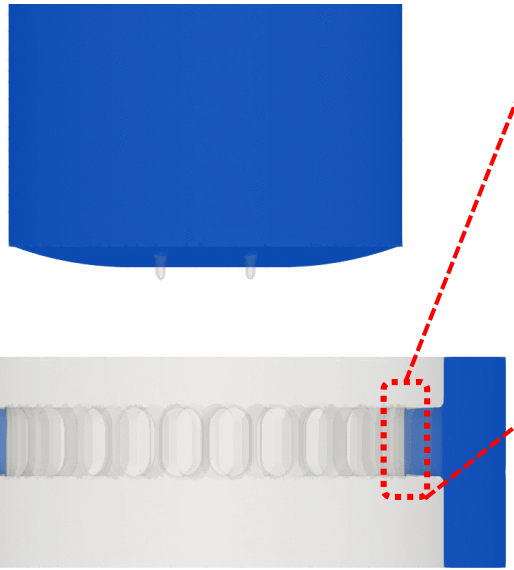
Methodology validation: 2-S Diesel marine engine

Two-strokes Diesel marine engine

Oxygen concentration

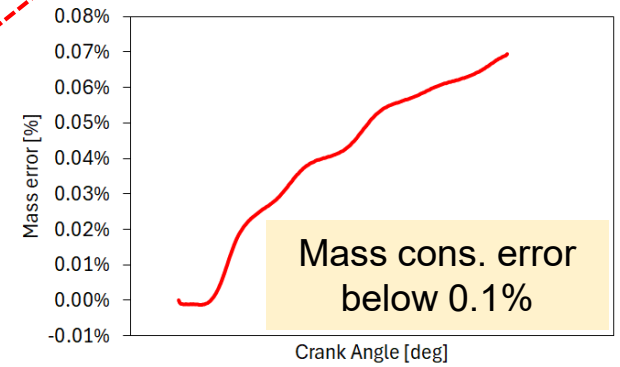


Velocity



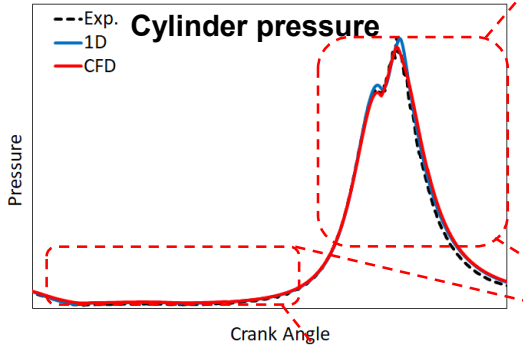
- ACMI coupling used for the inlet port opening
- Mass conservation error checked to be acceptable

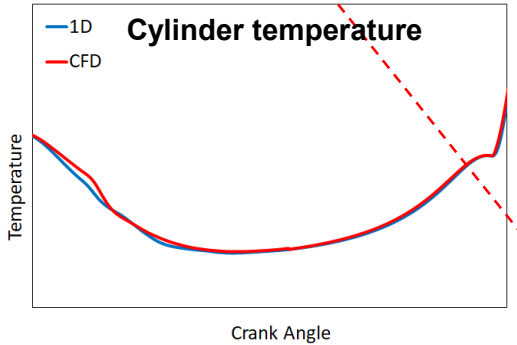
Mass conservation

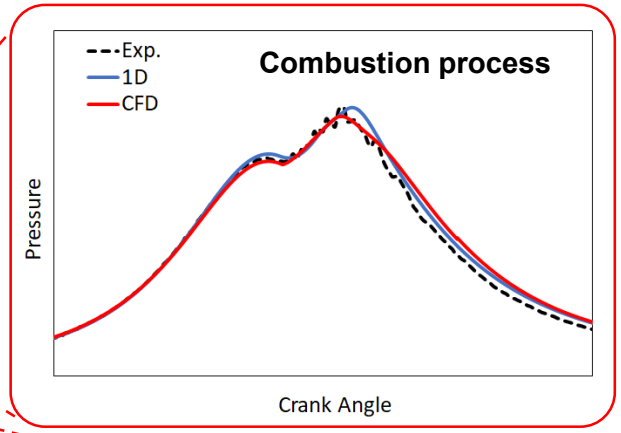


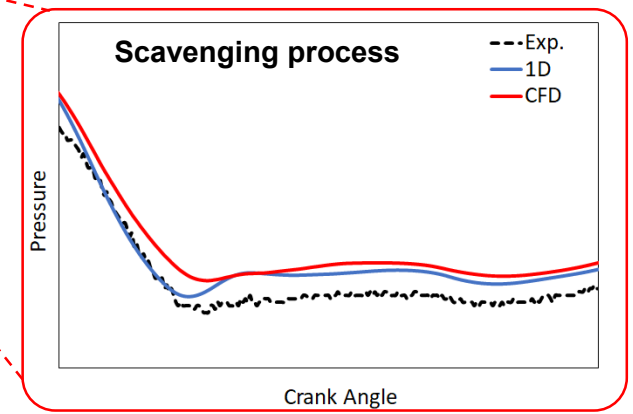
Methodology validation: 2-S Diesel marine engine

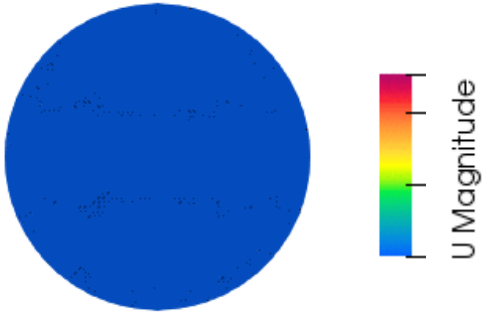
Results







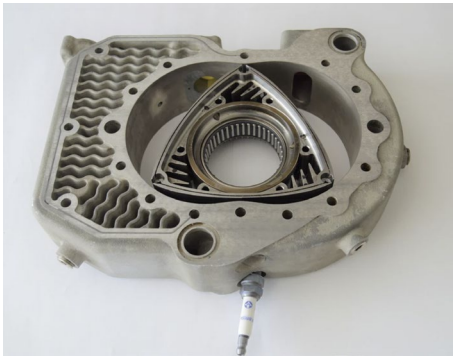




Good agreement in term of pressure peak amplitude and location with respect to experimental measurements

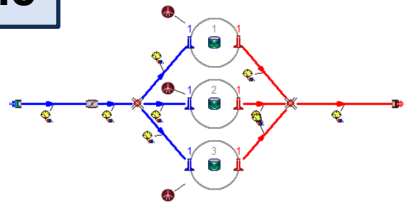
Rather good agreement with 1D simulation, similar trend with experiments except for an offset

Methodology validation: wankel engine



Wankel engine

Acknowledgment: ***T. Lucchini***

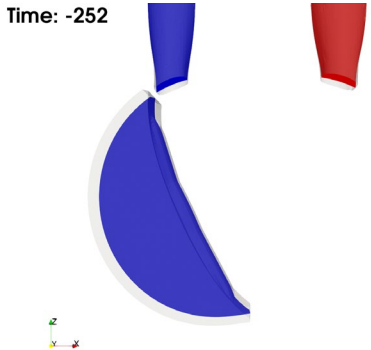


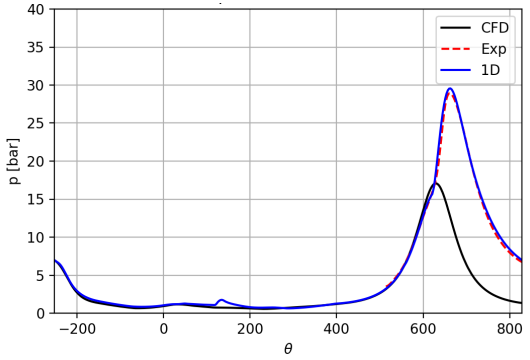
1D Gasdyn model supporting CFD simulations

Geometry data

Generating radius	~70 mm
Eccentricity	~11 mm
Width	~50 mm
Compression ratio	~10
Speed	7500 rpm

Validation – gas exchange

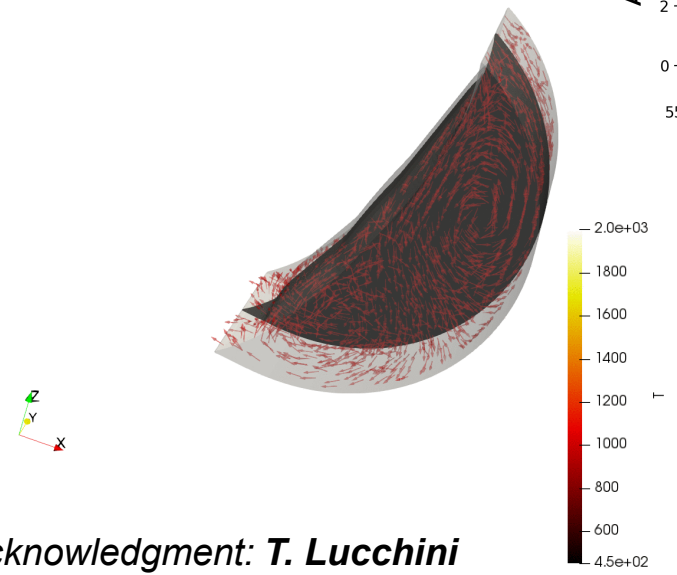


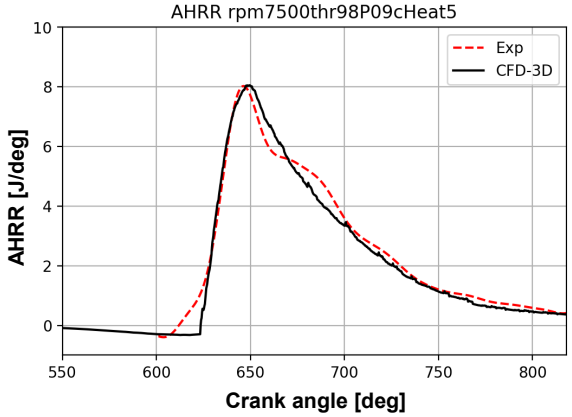


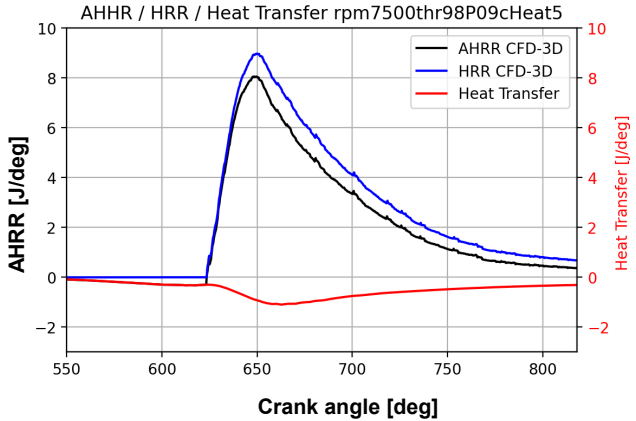
Methodology validation: wankel engine

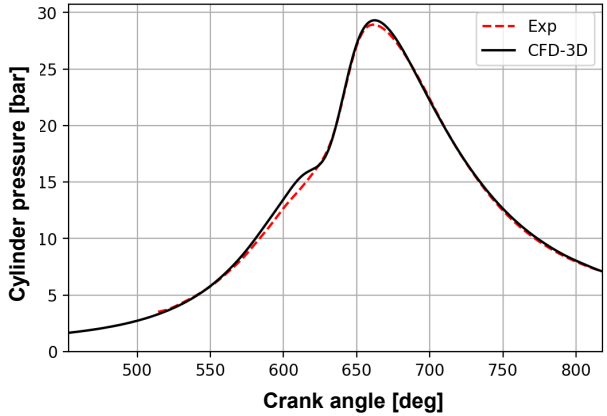
Validation – combustion

Time: 430.5









Heat transfer model: Angelberger, further tuned to match the cylinder pressure trace.

Need to further improve the heat transfer prediction:

- Near wall mesh resolution
- Modeling (including CHT)

Acknowledgment: ***T. Lucchini***

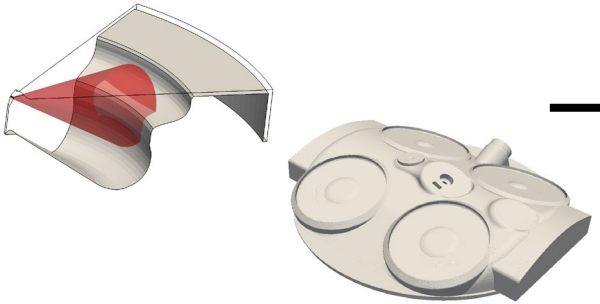
Lib-ICE : mesh management

Full-cycle simulation

LibICE
OpenFOAM

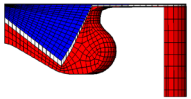
Multiple meshes approach

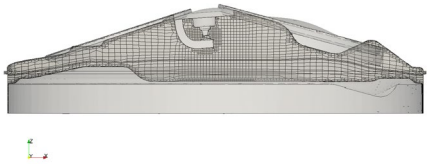
Power-cycle simulation



LibICE
OpenFOAM

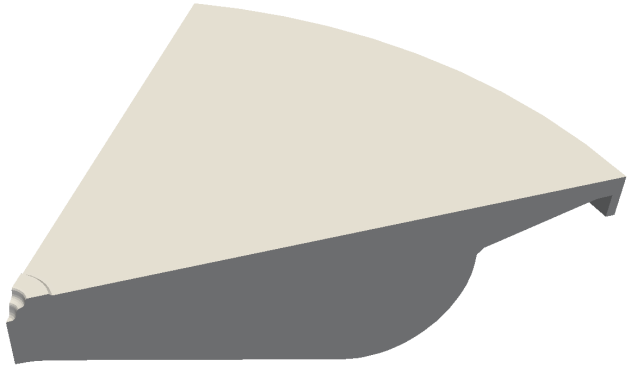
Dynamic-layering





Lib-ICE : power cycle simulation – dynamic layering

Wedge



- Used for axisymmetric combustion chamber with flat head
- Possibility to generate a jet-oriented grid

Full geometry

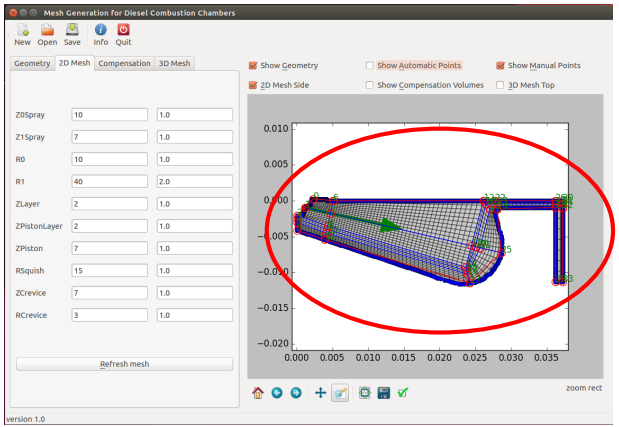
- Used for complex geometries with very detailed cylinder head and piston

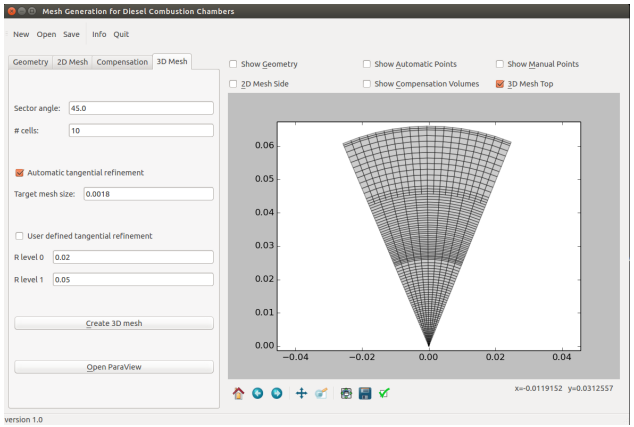
Lib-ICE : power cycle simulation – dynamic layering

Wedge

Python-based tool for mesh-generation

Time: -358 CAD





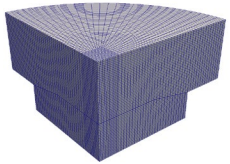
Mesh blocks are created in such a way to be consistent with the spray angle.

3D mesh of a sector is generated on the basis of user specifications.
Tangential refinement can be applied in order to keep constant the cell size.

Lib-ICE : power cycle simulation – dynamic layering

Full geometry

Background mesh using `blockMesh`



Mesh generation `snappyHexMesh`

Set-up mesh for moving process

Mesh moving

- Used for complex geometries with very detailed cylinder head and piston
- Easier way to perform closed-valve simulation since the gird is generated only once

Methodology validation: H_2 engine

Acknowledgment: ***F. Ramognino***

Hydrogen engine

- **4 conditions** investigated under variations of:
  - air-fuel ratio λ
  - load

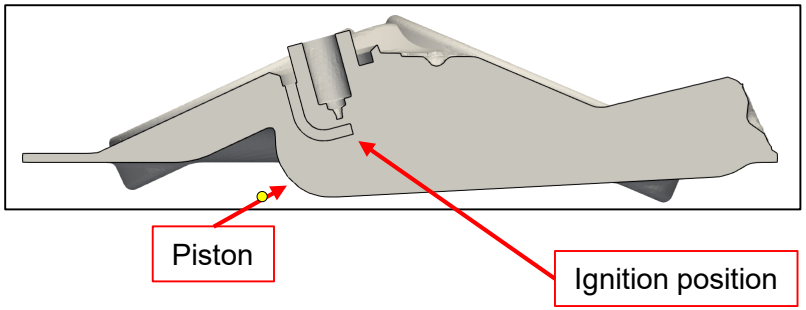
Feature	λ = 2.4 - ML	λ = 2.6 - ML	λ = 3.0 - ML	λ = 2.6 - HL
λ [-]	2.4	2.6	3.0	2.6
Spark timing [CAD]	-24.2	-26	-32	-30.2
IMEP [bar]	8.5	8.5	8.7	11.2

Data	Value	U.o.M.
Stroke	86	[mm]
Bore	84	[mm]
Compr. ratio	11:1	[-]
Speed	1500	[rpm]

- Each simulations included:
  - **a) Tumble initialization**
  - **b) Combustion**

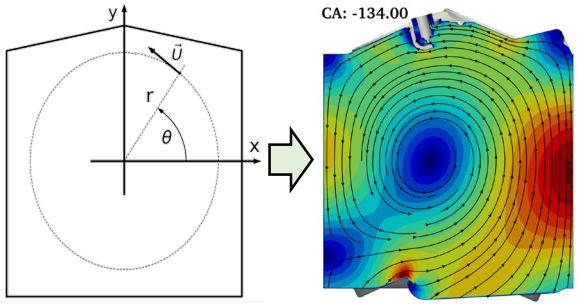
with **both 1D** (*Gasdyn*) and **3D-CFD** (*LibICE*) **approaches**

Cell size = 0.8 mm



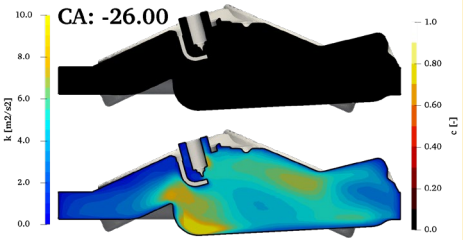
Methodology validation: H_2 engine

a) Tumble initialization



+ λ homog.

b) Combustion



Overall **satisfactory results** achieved with *both 1D and 3D approaches*

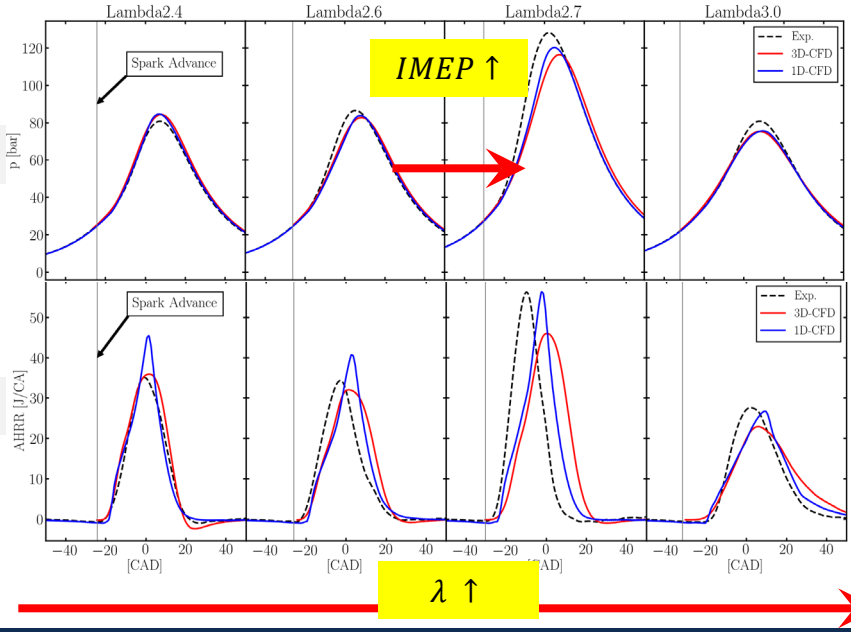
Acknowledgment: ***F. Ramognino***

Results

λ = 2.4 - ML | λ = 2.6 - ML | λ = 2.6 - HL | λ = 3.0 - ML

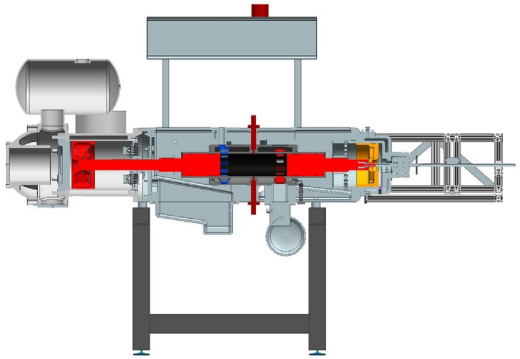
Pressure

AHRR



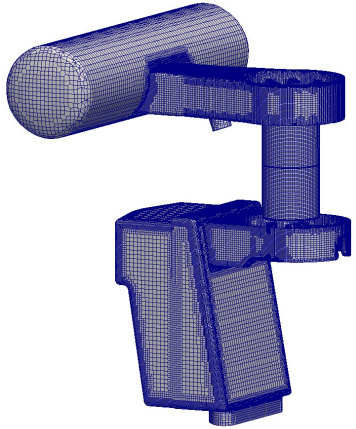
Methodology validation: free-piston engine

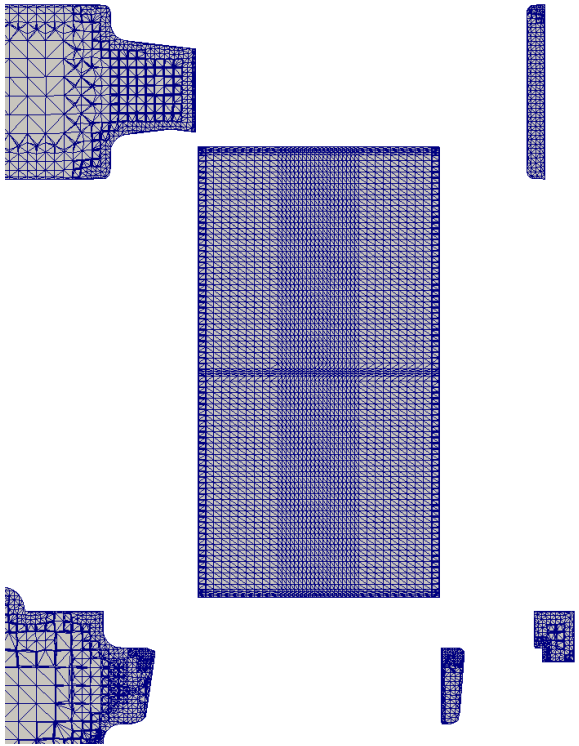
Free-piston engine



Data	Value	U.o.M.
Stroke	2x140	[mm]
Bore	108	[mm]
Compr. ratio	27:1	[-]
Frequency	20	[Hz]

- Flexible approach for mesh handling composed by:
  - **Dynamic layering**
  - **Mesh deformation**
  - **ACMI** coupling
- Max number of cells < 550k



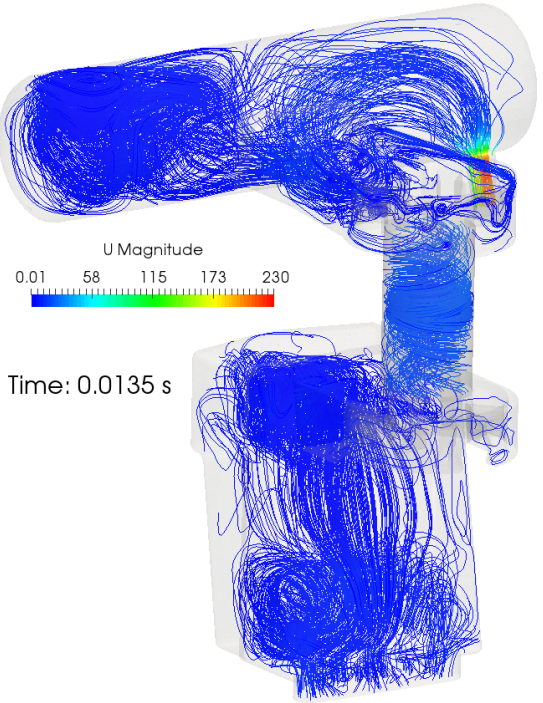


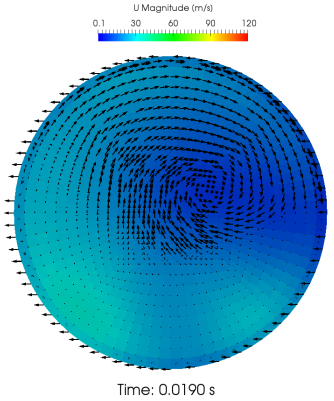
Methodology validation: free-piston engine

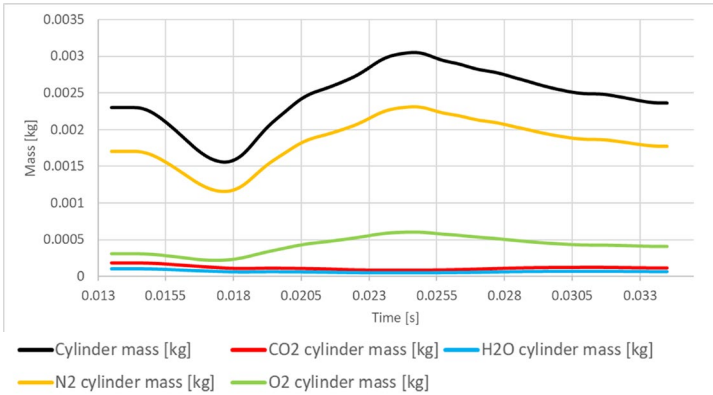
Results

- Gas-exchange simulations were performed to have a first estimation of the two main parameters for a 2S engine scavenging process
- Next steps: combustion simulations

Engine Parameters	Value
Charging Efficiency	78%
Cyl. Gas Purity	74%

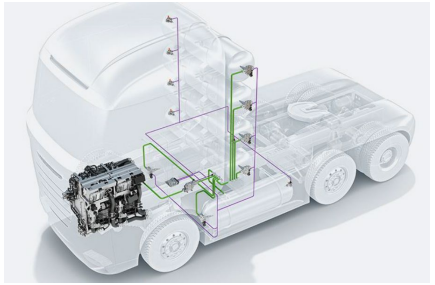


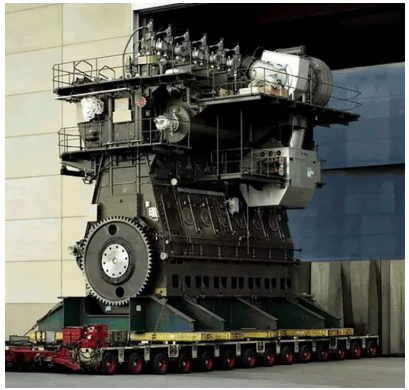


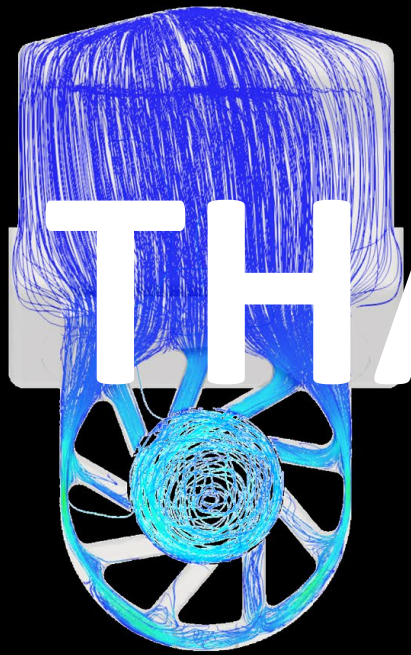


Conclusions

- **OpenFOAM + Lib-ICE** : consolidated and validated tool for the simulation of IC engines
- **Some improvement still needed**, research is going on
- **No need for external user-licence** programs
- **General and flexible approach** that can be applied to different engine configuration







THANK YOU

Giovanni Gianetti

Department of Energy, Politecnico di Milano

Via Lambruschini, 4a, 20156 Milano, Italy

giovannigaetano.gianetti@polimi.it