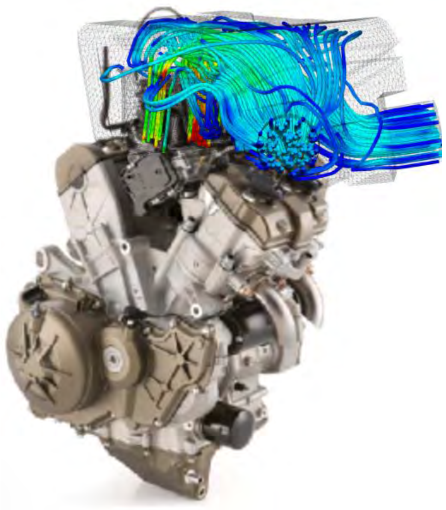
Modellazione CFD dei Motori a CI:
dal Cilindro ai Sistemi di Aspirazione e Scarico



A. Onorati, G. D'Errico, G. Ferrari, G. Montenegro, T. Lucchini,
F. Piscaglia, T. Cerri, A. Montorfano, A. Della Torre et al.

Internal Combustion Engine Group
Department of Energy, Politecnico di Milano

ICE GROUP POLITECNICO DI MILANO

The Internal Combustion Engine Group

Staff

Angelo Onorati, Full Professor
Gianluca D'Errico, Associate Professor
Gianluca Montenegro, Associate Professor
Tommaso Lucchini, Associate Professor
Federico Piscaglia, Associate Professor
Giancarlo Ferrari, Retired Professor

Post-doc researchers

Tarcisio Cerri, post-doc researcher
Augusto Della Torre, RTDa, post-doc res.
Andrea Montorfano, RTDa, post-doc res.

PhD students

Amin Maghbouli
Lorenzo Nocivelli
Isabella Verri
Lorenzo Sforza
Filippo Giussani
Keyvan Shaabani
Ehsan Tamasebi
Yan Wu
Javier Rubio
Davide Paredi

MSc thesis

15 – 20 per year

Visiting PhD

Aalto, Sidney, KTH, Chalmers, Freiberg, Valencia, etc.,

ICE GROUP POLITECNICO DI MILANO

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MSc thesis

15 – 20 per year

Visiting PhD

Aalto, Sidney, KTH, Chalmers, Freiberg, Valencia, etc.,

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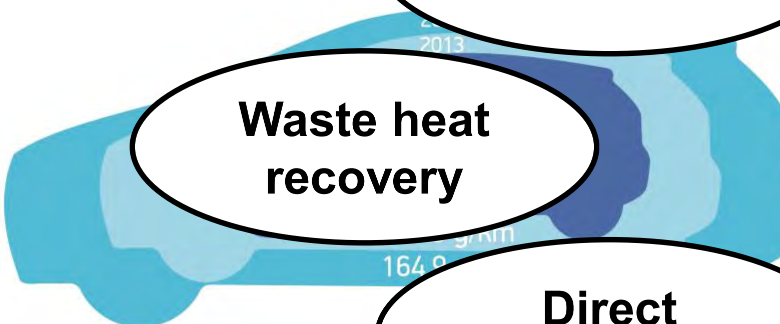
Background

Internal combustion engine development will never stop!

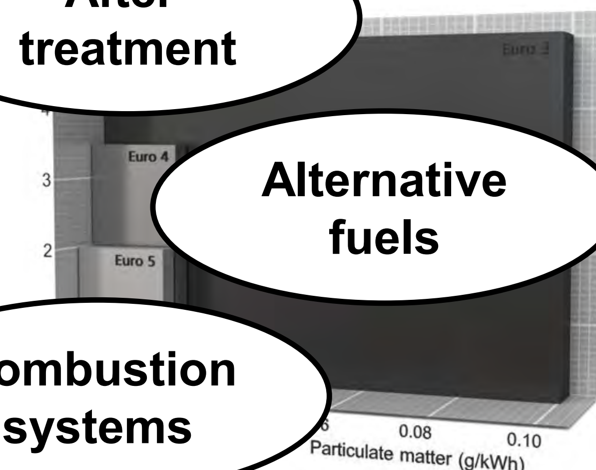
Efficiency increase

- Downsizing
- Waste heat recovery
- Direct injection



Pollutant emission control

- After-treatment
- Alternative fuels
- Combustion systems

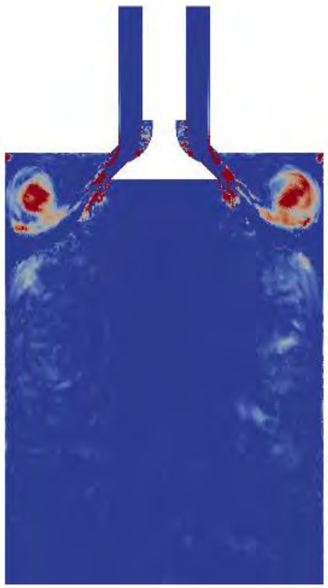


Research arguments at PoliMi

Main research topics

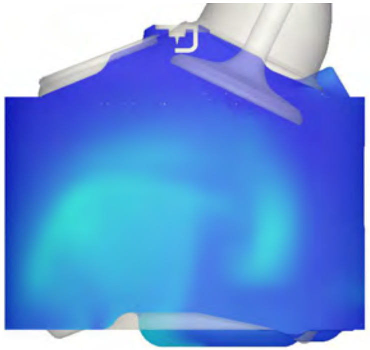
CFD simulation of IC engines:

- combustion and emissions;
- GDI and Diesel sprays;
- alternative fuels for I.C. engines;
- reacting flows and after-treatment devices (SCR, DPF);
- Large Eddy Simulation of engine-like geometries;
- integrated 1D-3D fluid-dynamic models;
- 1D thermo-fluid dynamic modeling;
- noise and acoustics.



CFD code: OpenFOAM/Lib-ICE

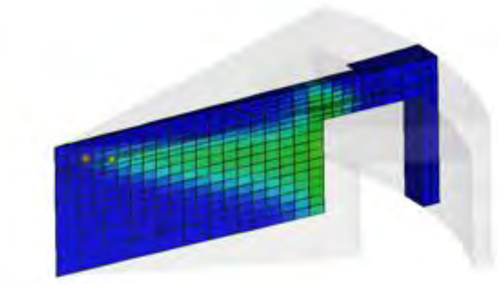
- **OpenFOAM is a free-to-use Open Source numerical simulation software** with extensive CFD and multi-physics capabilities, written in a highly efficient C++ object-oriented programming.



- Free-to-use, allows to exploit high parallelization with only hardware costs.

- Ideal platform for research collaborations.

- Very wide diffusion with 2000 downloads/week.

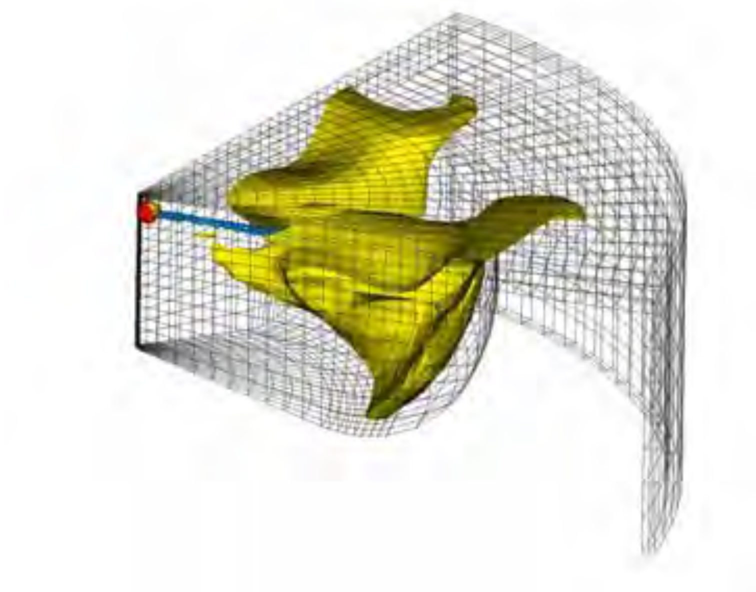


- We started to work with OpenFOAM in 2000. Our group is currently involved in several activities in Europe, concerning **OpenFOAM** development and applications.

CFD code: OpenFOAM/Lib-ICE

The ICE group of Politecnico di Milano has contributed to develop the engine library under **OpenFOAM** technology (Lib-ICE):

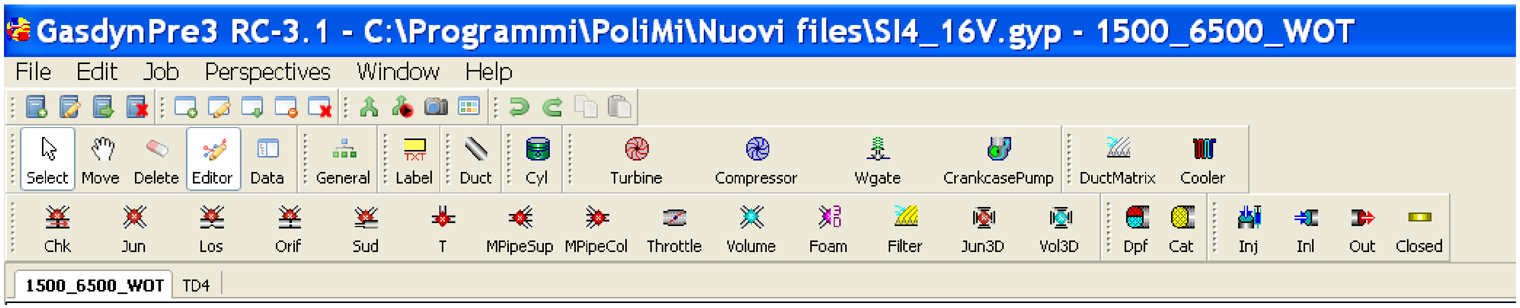
- Moving mesh algorithms
- Spray modeling
- Combustion process modeling
- DPF and SCR modeling
- 1D-3D coupling interface
- Non-linear acoustics modeling

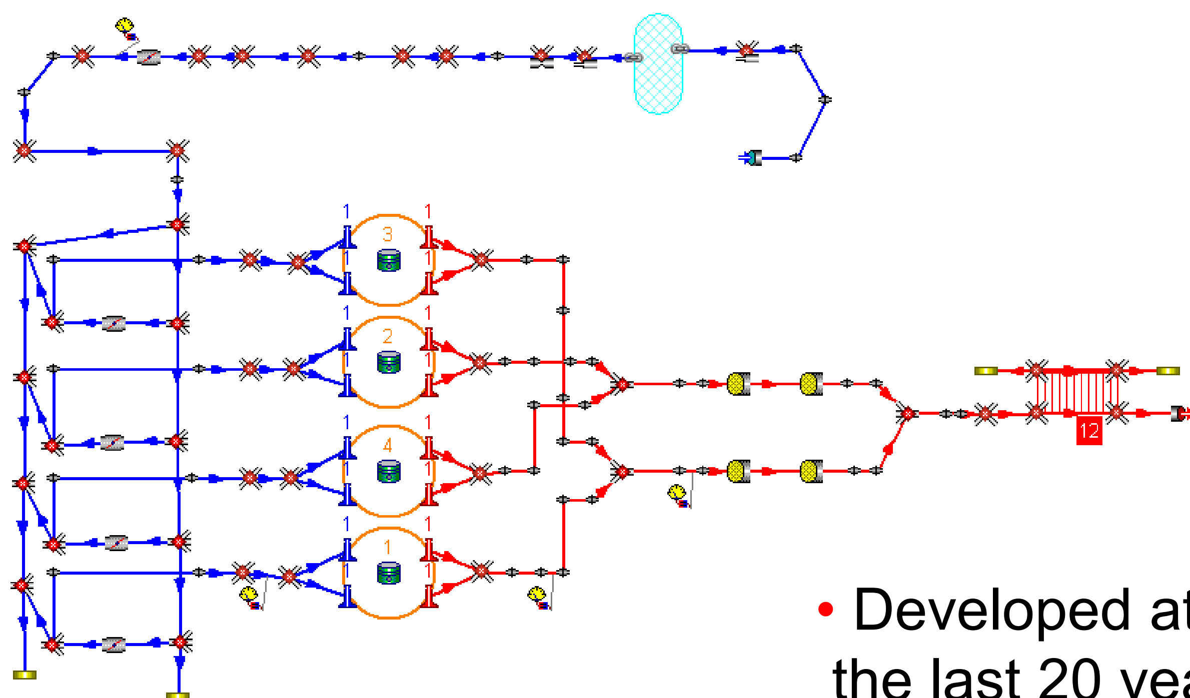


Tool:

- in-house CFD libraries and solvers (**Lib-ICE**) developed under the **OpenFOAM®** technology.

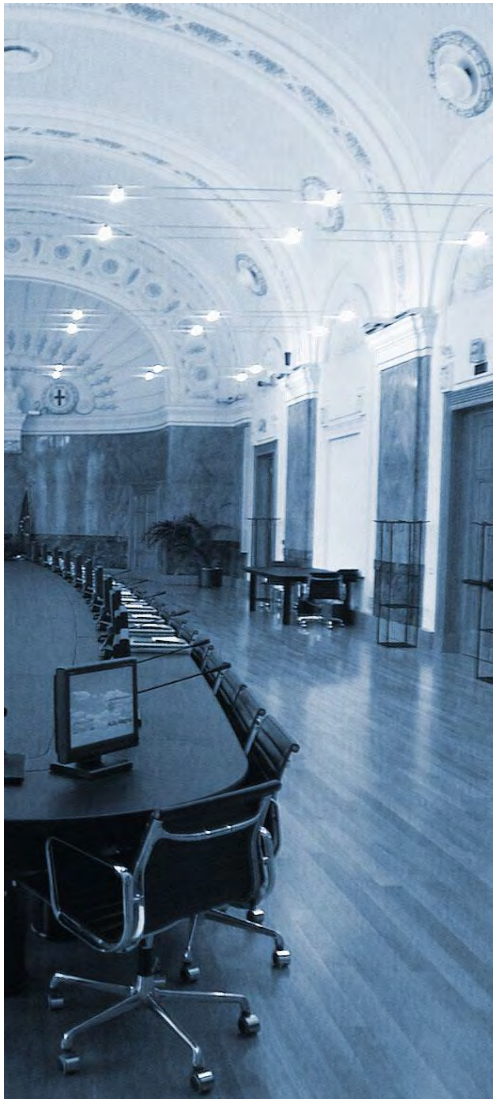
1D simulation code: GASDYN





- Developed at PoliMi during the last 20 years.

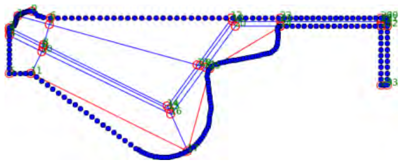
Academic collaborations

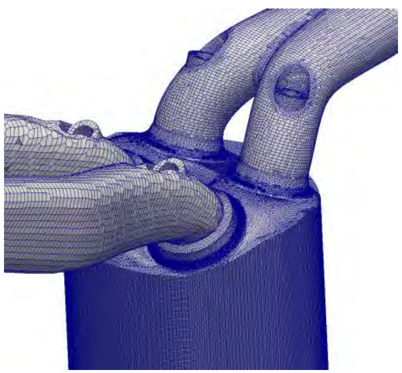


Argonne National Labs
Chalmers University
ETH - Zurich
Freiberg University
Istituto Motori - CNR Naples
Imperial College
KTH – Royal Institute of Technology
Lund University
Michigan Tech University
Ohio State University (CAR)
University of Bologna
University of Firenze
University of Genova
University of Valencia (CMT)

OpenFOAM at PoliMi (Lib-ICE)

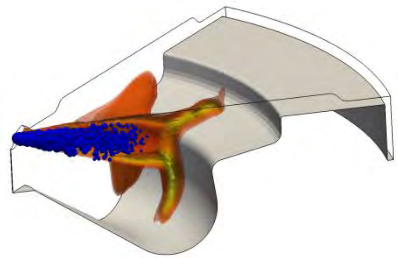
Pre-Processing

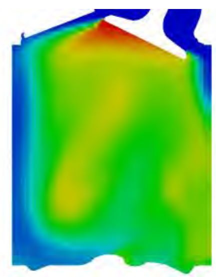




Automatic mesh generation

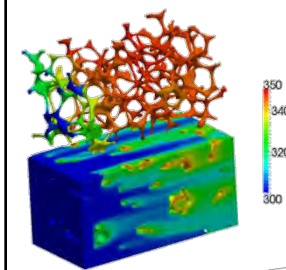
In-cylinder flows & combustion

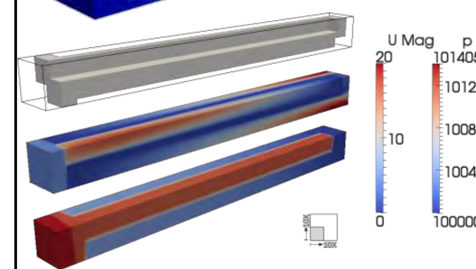




Gas exchange, fuel air mixing
SI, CI, PCCI, HCCI combustion

After-treatment

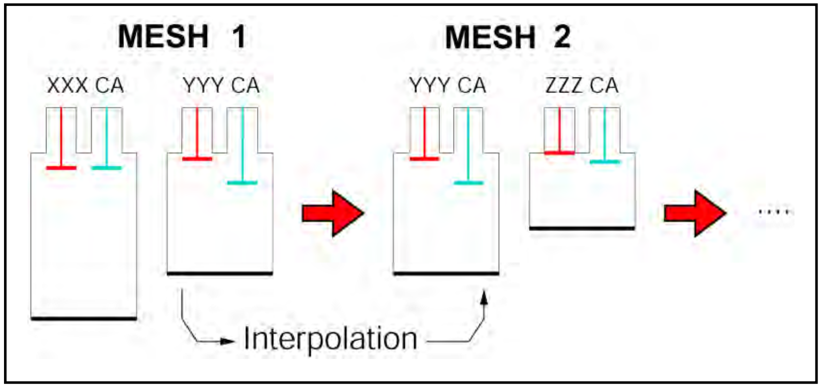




After-treatment modeling
SCR, DPF, TWC, DOC

In-cylinder mesh management

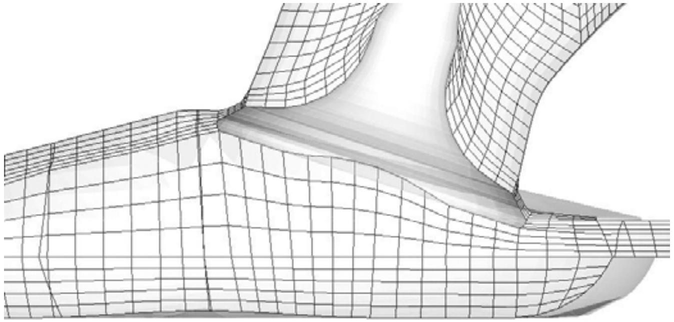
- **Multiple meshes** cover the entire simulation (each mesh is valid for a certain crank angle interval).
- **Mesh to mesh interpolation** automatically performed.



- **Grid points** moved by means of an **automatic mesh motion** solver. Possibility to combine **automatic mesh motion** and **topological changes**.

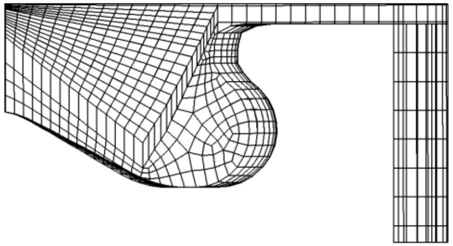
Automatic mesh motion

$$\nabla^2(\gamma \mathbf{u}) = 0 \longrightarrow \mathbf{x}_{new} = \mathbf{x}_{old} + \mathbf{u}\Delta t$$

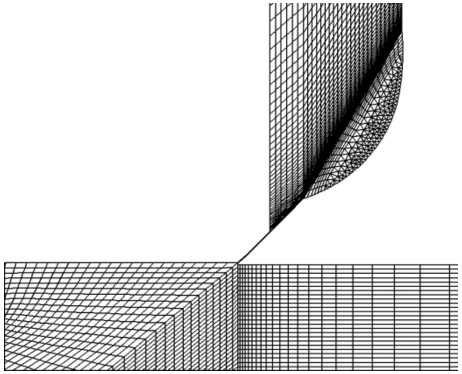


Topological changes

Dynamic layering



Sliding interface

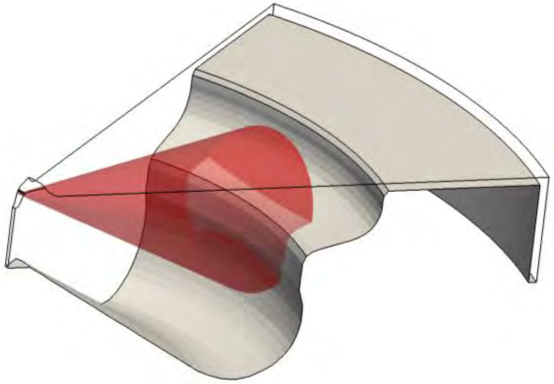


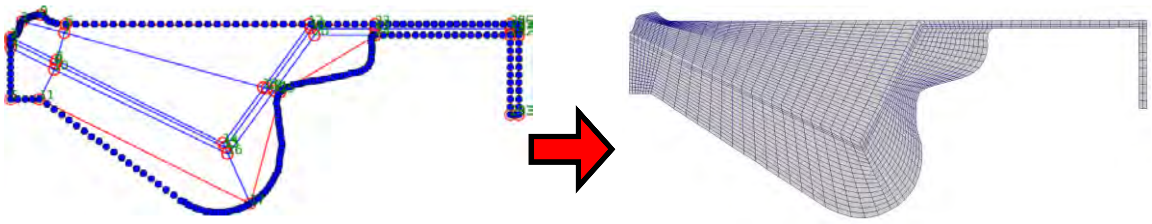
Automatic mesh generation

Combustion chambers for Diesel Engines

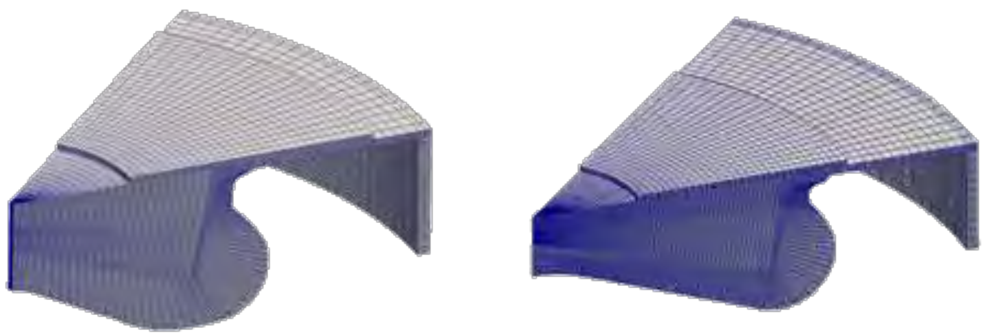
Input data:

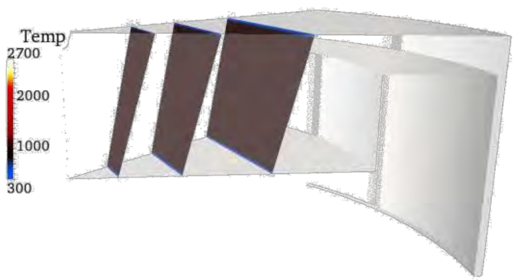
- Piston bowl points
- Injection angle





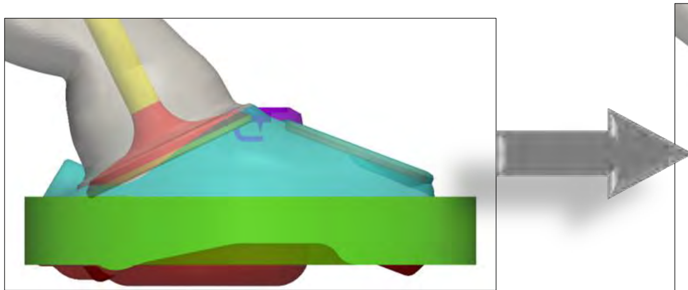
Fully-hexaedral spray-oriented mesh

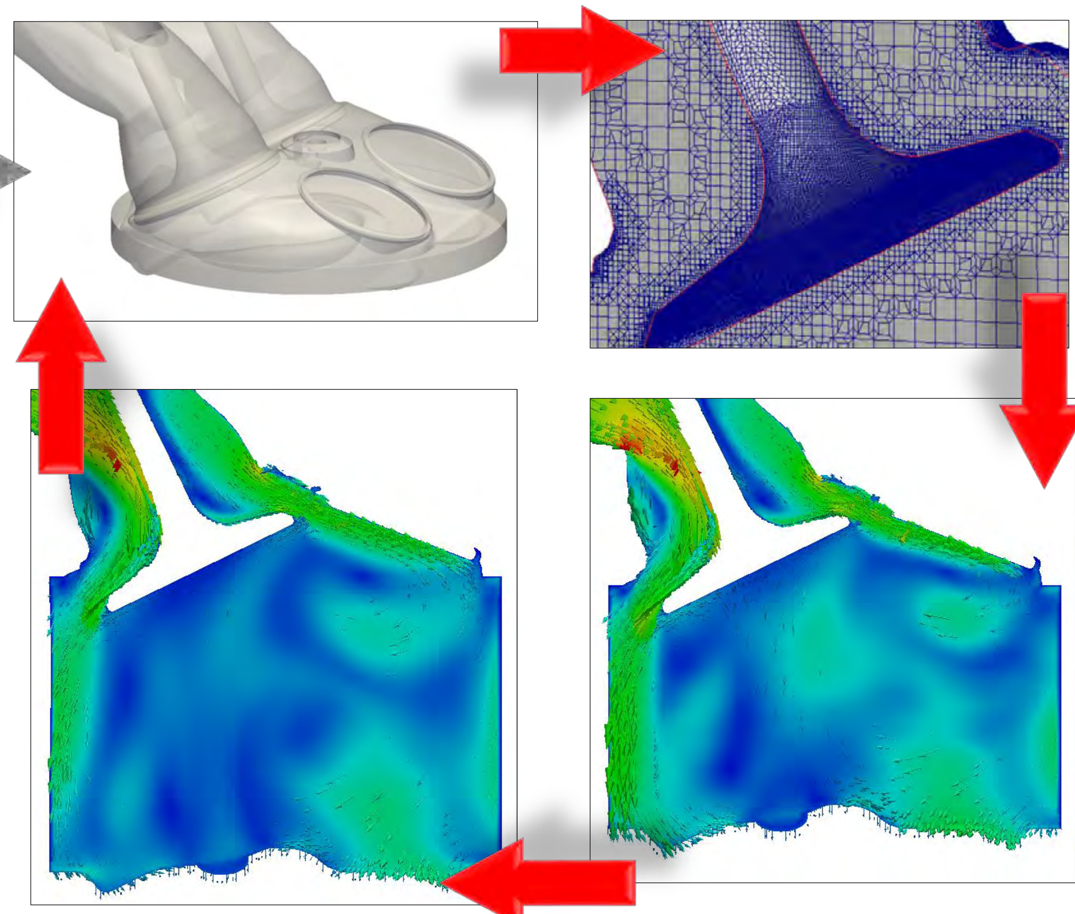




Automatic mesh generation

Combustion chambers for S.I. engines

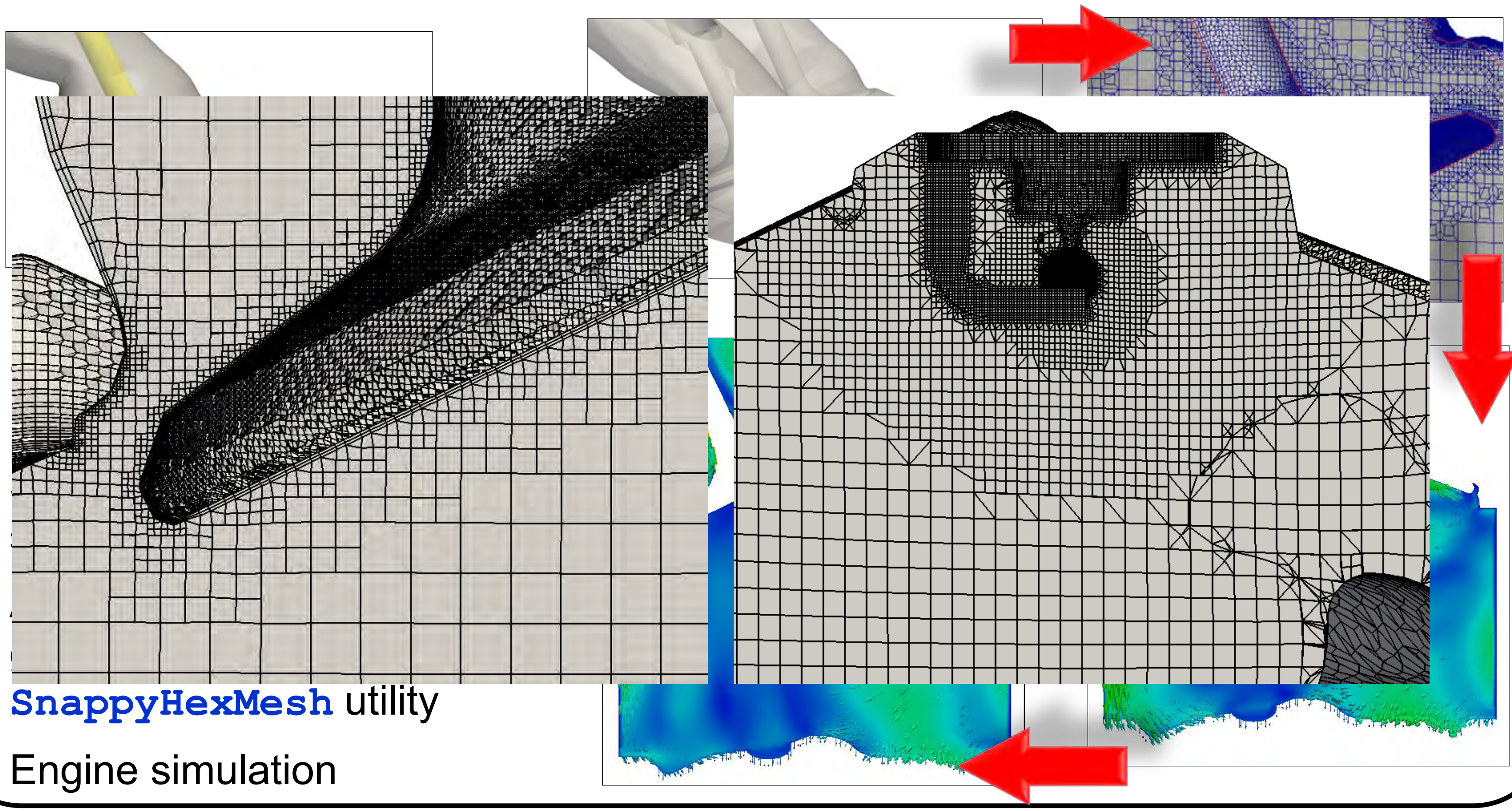




- CAD geometry pre-processing
- STL mesh building at specified target CAD
- Automatic finite volume mesh generation with **SnappyHexMesh** utility
- Engine simulation

Automatic mesh generation

Combustion chambers for S.I. engines

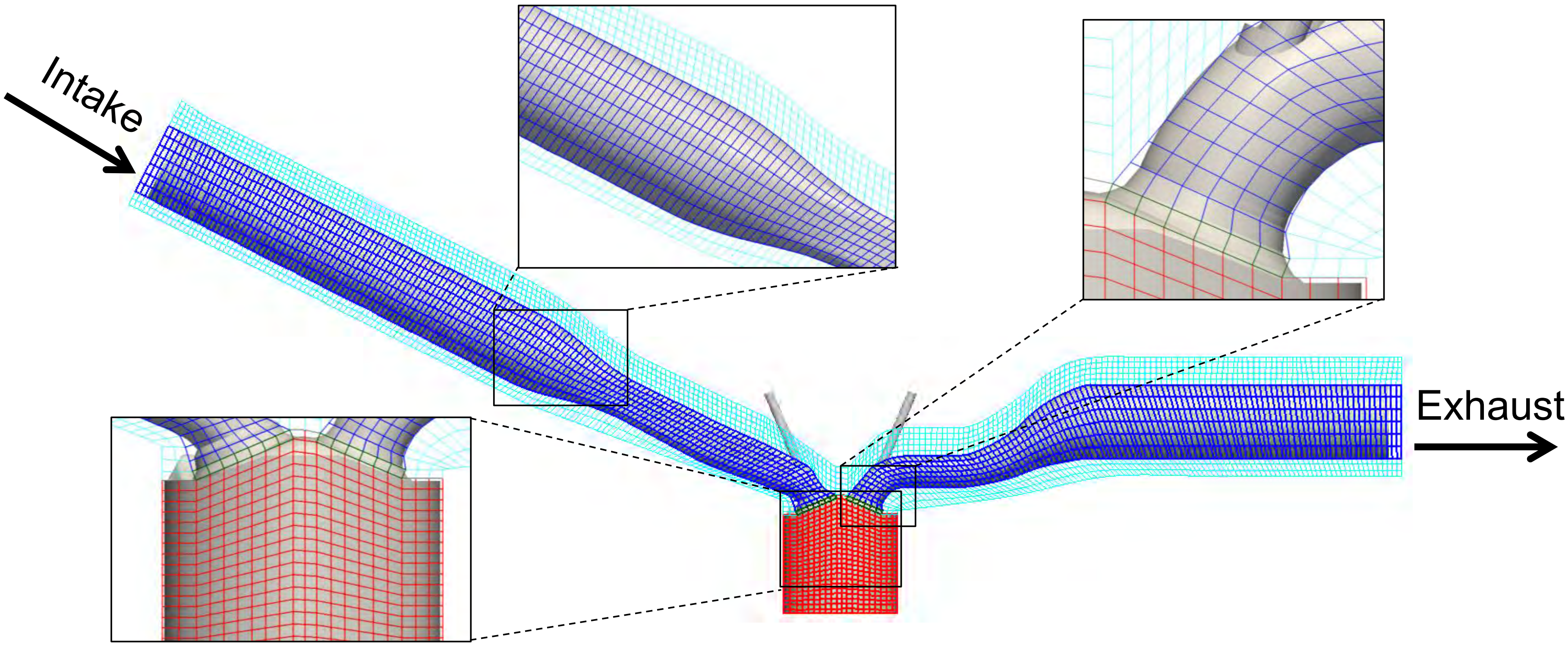


-
-
-
SnappyHexMesh utility
- Engine simulation

Automatic mesh generation

Validation: Darmstadt engine

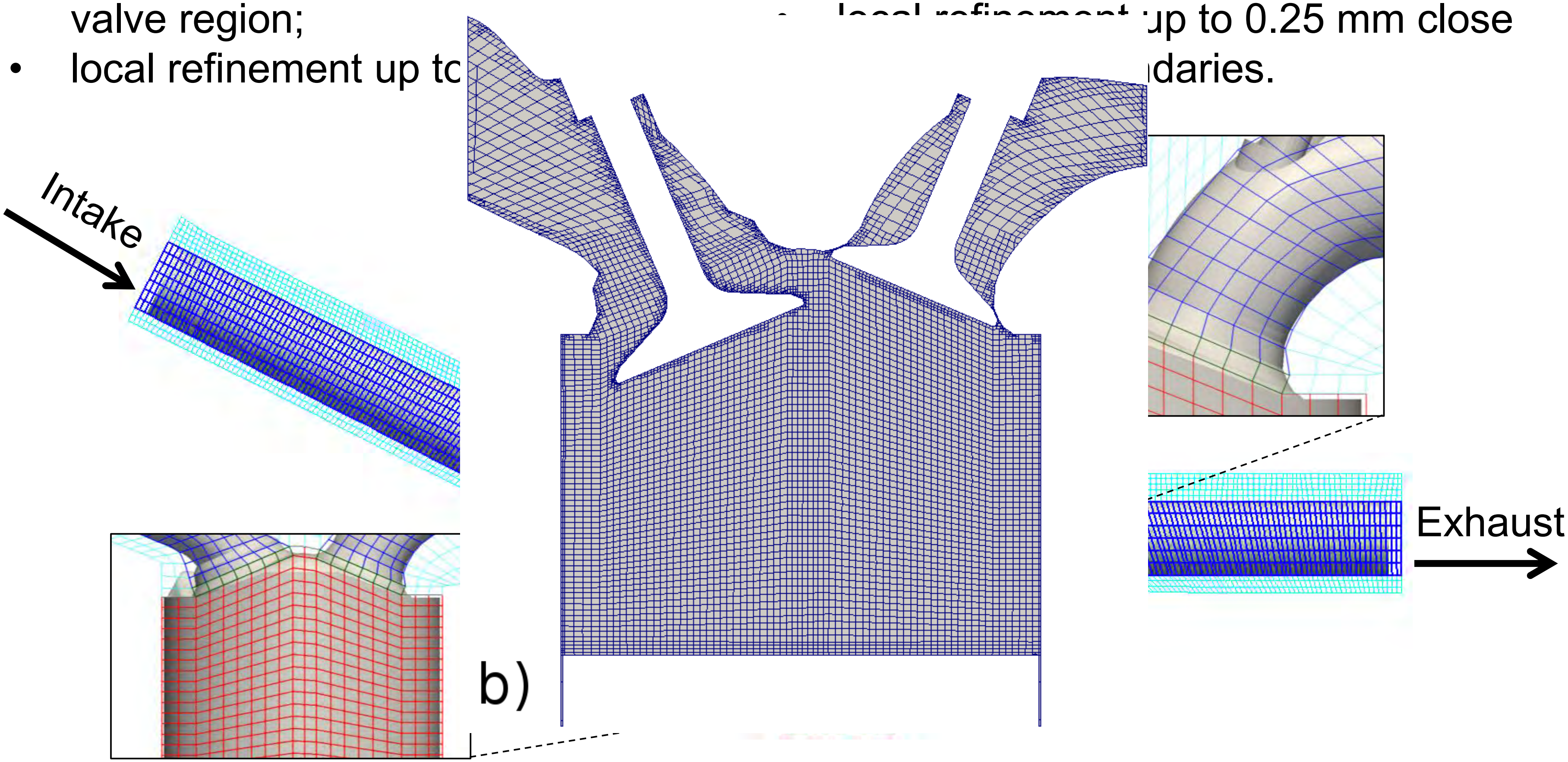
- 4 mm mesh size in the ducts region;
- 2 mm mesh size in the cylinder and valve region;
- local refinement up to 1 mm close to cylinder head, piston and liner boundaries;
- local refinement up to 0.25 mm close to the valve boundaries.



Automatic mesh generation

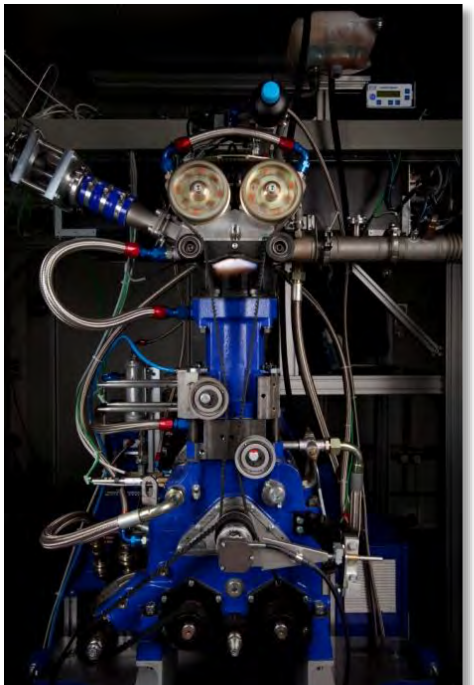
Validation: Darmstadt engine

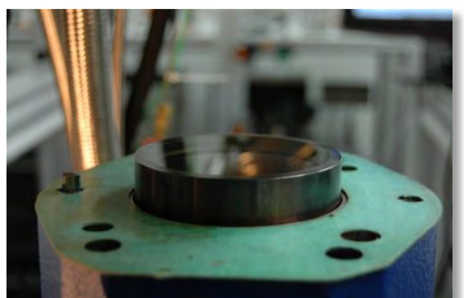
- 4 mm mesh size in the ducts region;
- 2 mm mesh size in the cylinder and valve region;
- local refinement up tc
  cylinder head, piston and liner boundaries;
- local refinement up to 0.25 mm close
  daries.



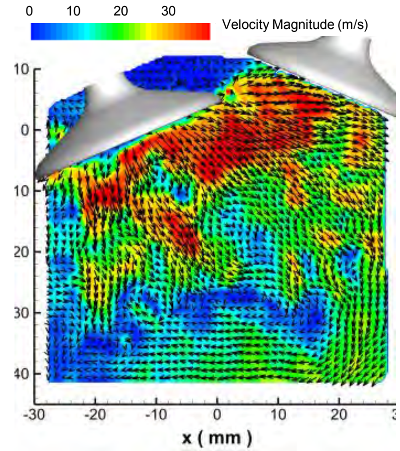
Automatic mesh generation

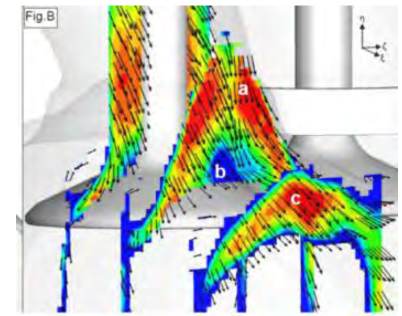
Validation: Darmstadt engine





Four-valve engine, fully optically accessible.





- PIV measurement techniques:
  - low repetition rate planar PIV
  - high-speed PIV (HS-PIV)
  - stereoscopic PIV (SPIV)
  - tomographic PIV (TPIV).

for a detailed characterization of the average in-cylinder flow-field and related fluctuations.

Acknowledgments: Dr. Brian Peterson, Dr. Benjamin Böhm, PhD student Carl-Philipp Ding and prof. Andreas Dreizler (TU Darmstadt)

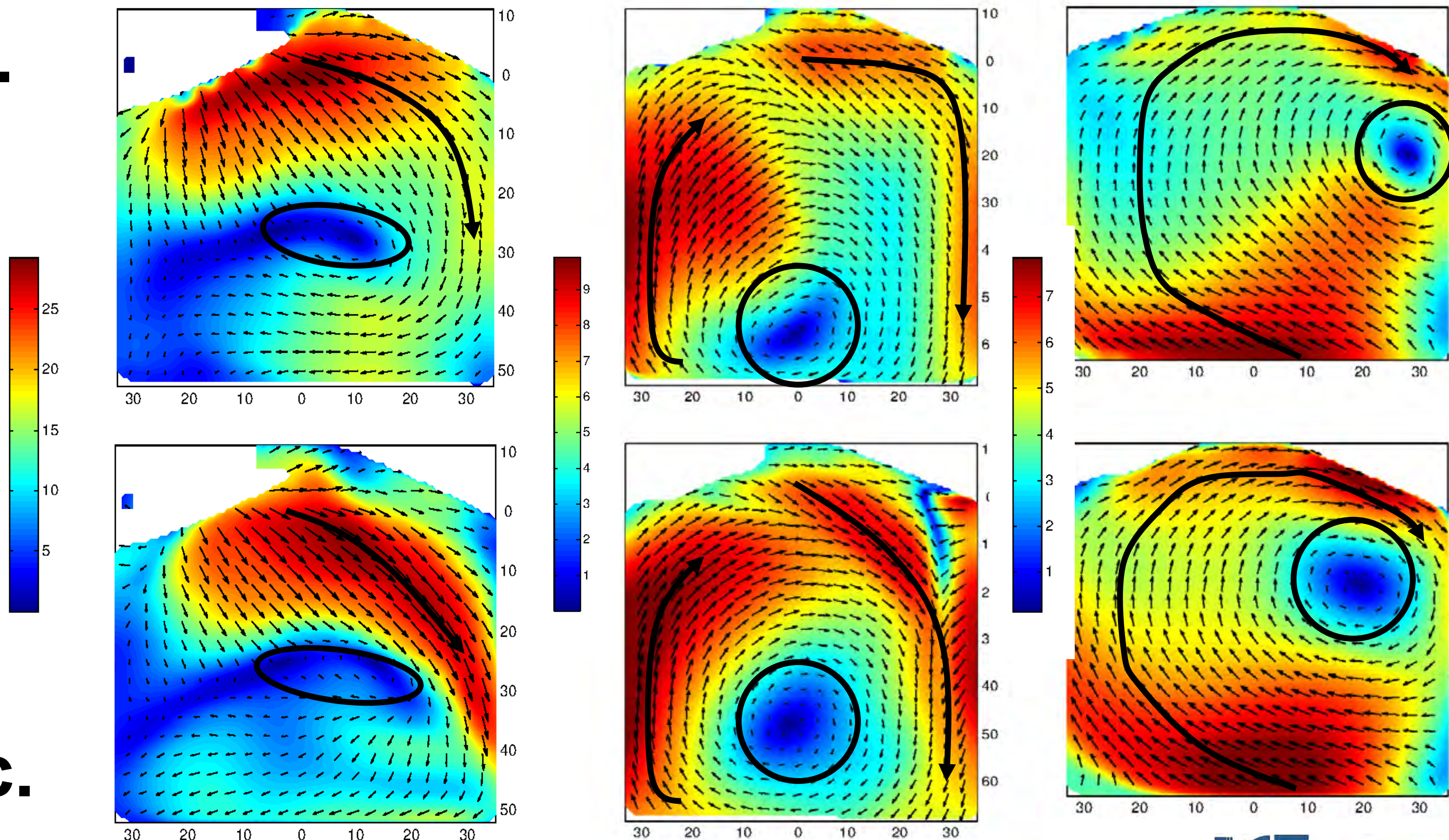
Automatic mesh generation

Validation: Darmstadt engine

450 CAD | 540 CAD | 630 CAD

Exp.

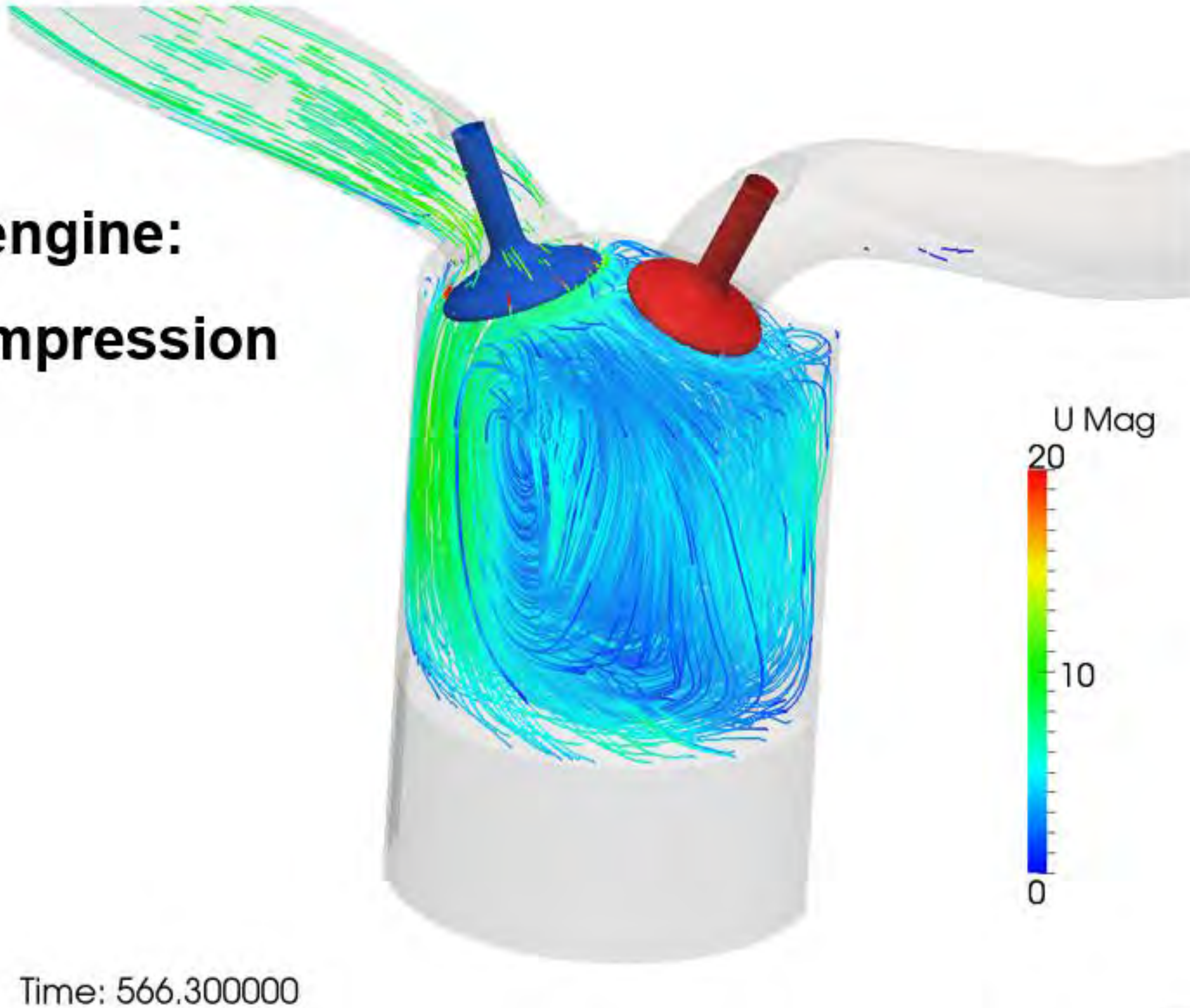
Calc.



Automatic mesh generation

Darmstadt engine:

intake & compression phases

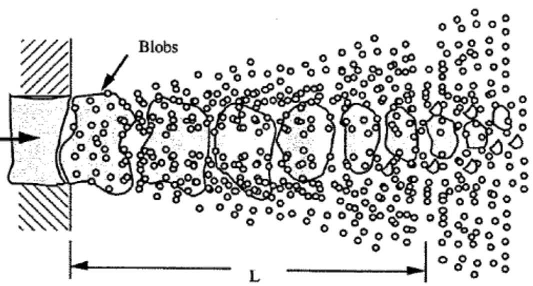


Spray and wall-film modeling

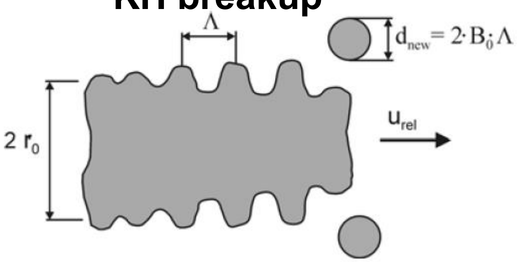
New sub-models for multi-hole nozzles

- **Injection**: Huh, Reitz-Bracco, Nurick
- **Atomization** : Huh-Gosman, Bianchi
- **Breakup**: KHRT
- **Wall-interaction**: Bai and Gosman, Stanton and Rutland
- **Evaporation**: based on Spalding mass number

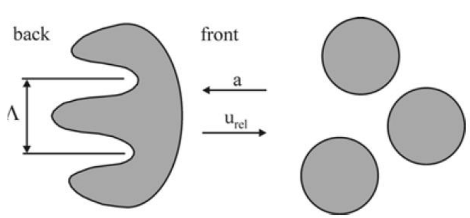
Blob injection



KH breakup

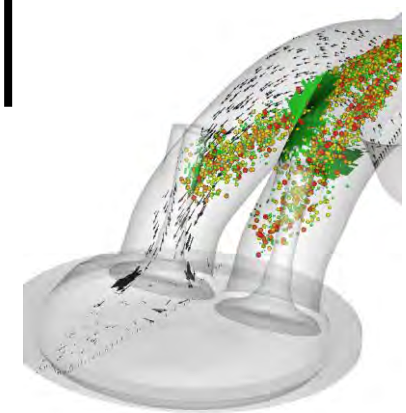


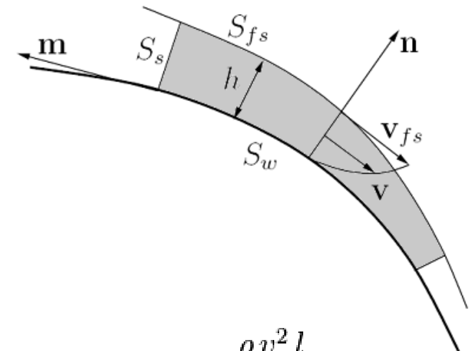
RT breakup



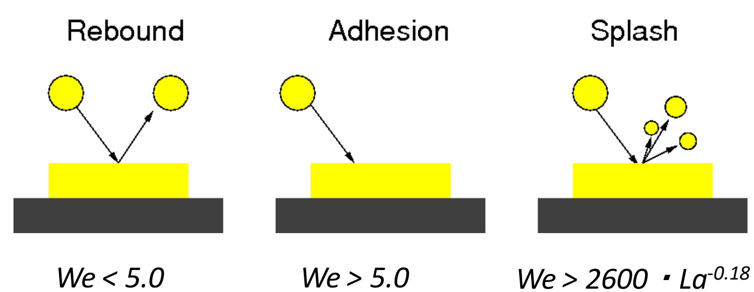
Wall-film model (finite-area)

- Mass, momentum and energy equations for the liquid film solved on mesh boundary.





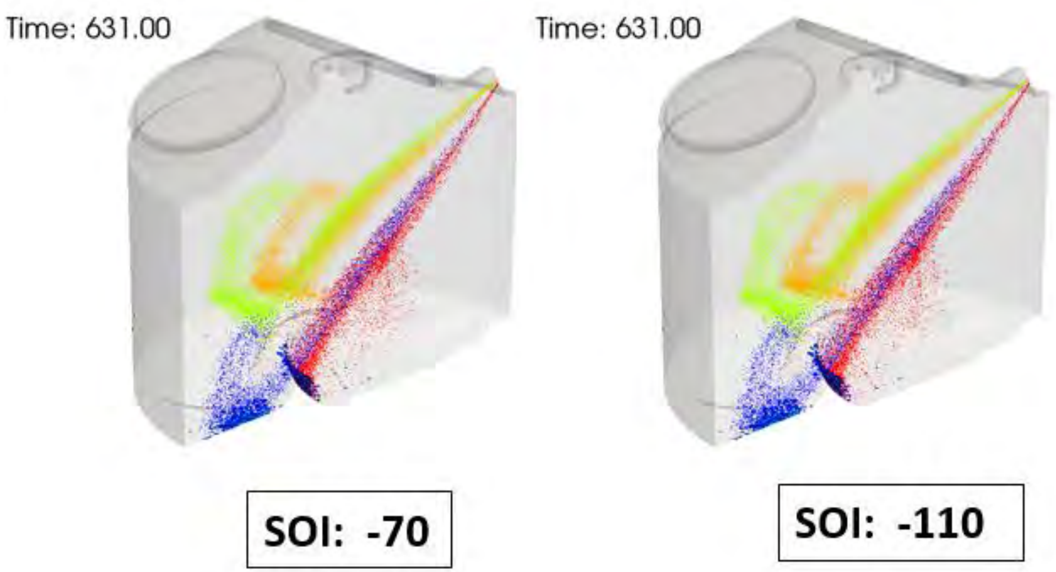
$$\mathrm{We} = \frac{\rho v^2 l}{\sigma}$$

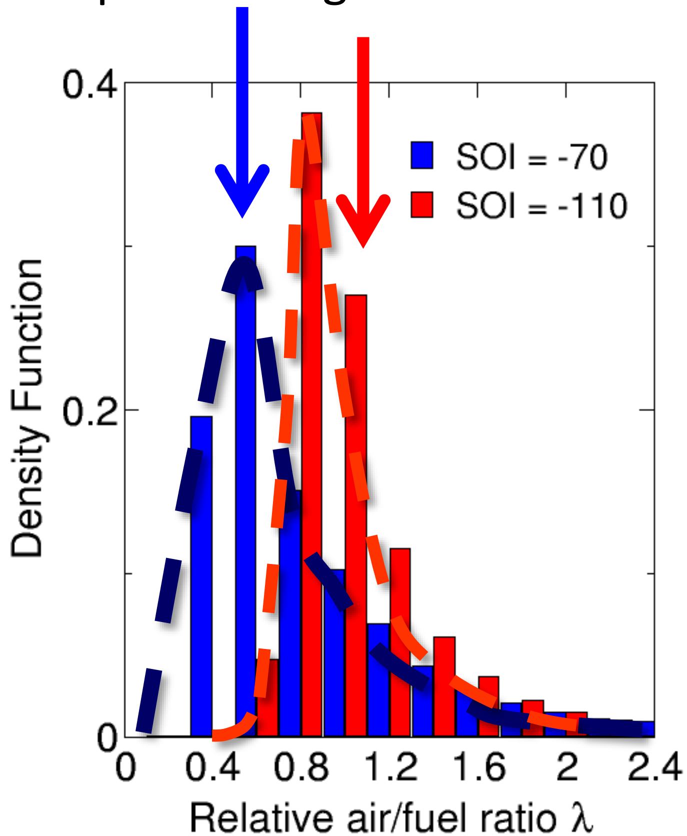


GDI engine case study

Fuel-air mixing modeling: stratified charge GDI engine, spray and wall film evolution at 100 bar

- SOI effect on relative air/fuel ratio distribution at spark-timing





Acknowledgments: Dr. Vaglieco, Ing. Sementa, Dr. Allocca, Ing. Montanaro (CNR-IM)

GDI engine simulations

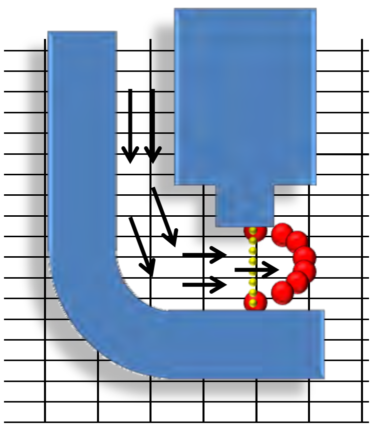
Full-cycle simulation of GDI engines

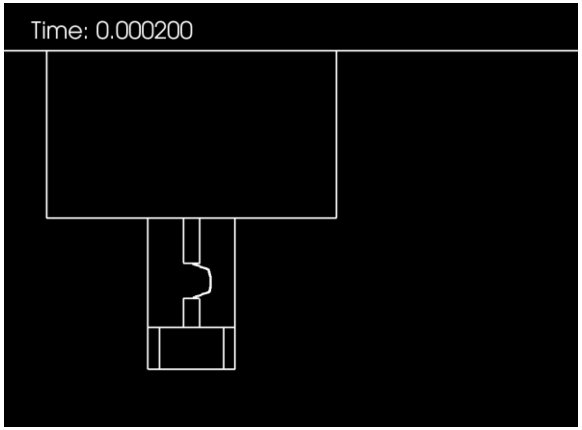
This work was sponsored and carried out in collaboration with MAGNETI MARELLI

Acknowledgments: Ing. Di Gioia, Dr. Bonandrini, Ing. Venturoli (Magneti Marelli)

Spark-ignition combustion models

- Detailed description of the **flame kernel growth process via Lagrangian approach** and suitable sub-models (breakdown, electrical circuit, wrinking)
- **Coherent flamelet model** for flame propagation in the **Eulerian phase** (gas)
- Strict coupling between **Eulerian and Lagrangian phases**.





Coherent Flamelet Model (CFM) for combustion:

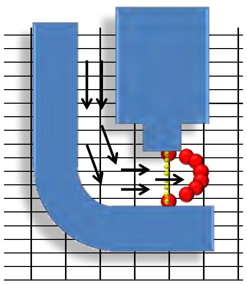
$$\frac{\partial \rho \Sigma}{\partial t} + \frac{\partial \rho u_i \Sigma}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\frac{\mu}{Sc} + \frac{\mu_t}{Sc_t}\right)\frac{\partial \Sigma}{\partial x_i}\right] + P \cdot \Sigma - D \cdot \Sigma + P_k$$

(Flame surface density transport equation)

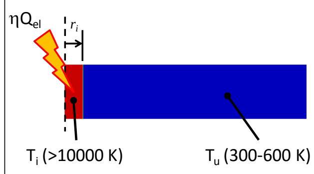
Spark-ignition combustion models

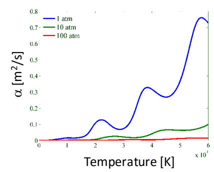
Comprehensive model from flame kernel formation to turbulent combustion

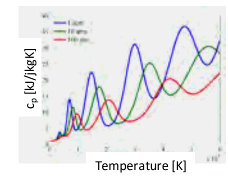
1) The spark channel is represented by a set of Lagrangian particles, convected by the mean flow.



4) Initial thermal transient of the plasma channel correctly described by solving the heat conduction equation on it.



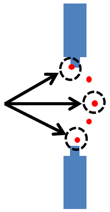




$$\frac{\partial T_{pl}}{\partial t} = \alpha \cdot \nabla^2 T_{pl} + \frac{\eta \cdot \dot{Q}_{el}}{\rho c_p V_{pl}} = \alpha \cdot \nabla^2 T_{pl} + \frac{\eta \cdot V(t) \cdot i(t)}{\rho c_p V_{pl}}$$

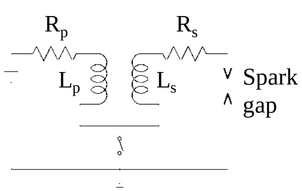
2) Flame kernels are launched at the particle locations satisfying the ignition criterion (Karlovitz). For each particle mass and energy equations are solved.

$$Ka < Ka_\delta$$



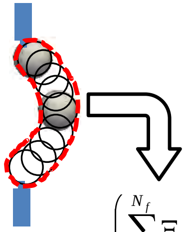
$$\frac{dm_p}{dt} = 4\pi r_p \rho_u \left(s_t + \frac{\rho_p}{\rho_u} s_{plasma} \right) \qquad \frac{dT_p}{dt} = -\frac{m_p}{\dot{m}_p}\left(T_p - T_b\right) + \frac{\eta \cdot \dot{Q}_{spk}}{m_p \cdot c_{p,p}}$$

5) Simplified model for the secondary circuit to estimate the amount of energy transferred to the gas phase



$$\begin{cases} \dfrac{dE_s}{dt} = -R_s \cdot i_s(t)^2 - V_s(t) \cdot i_s(t) \\ i_s(t) = \sqrt{\dfrac{2E_s}{L_s}} \\ V_s(t) = V_{ac} + V_{gc}(l_{spk}) \\ \dot{Q}_{spk} = V(t) \cdot i(t) \end{cases}$$

3) Flame surface density distribution reconstructed from particle distribution and their size.



$$\Sigma_{spk} = \frac{\left(\sum_{i=1}^{N_f} \Xi_i \cdot S_i \right)}{V_{cell}}$$

6) Ignition source term included in the flame surface density transport equation:

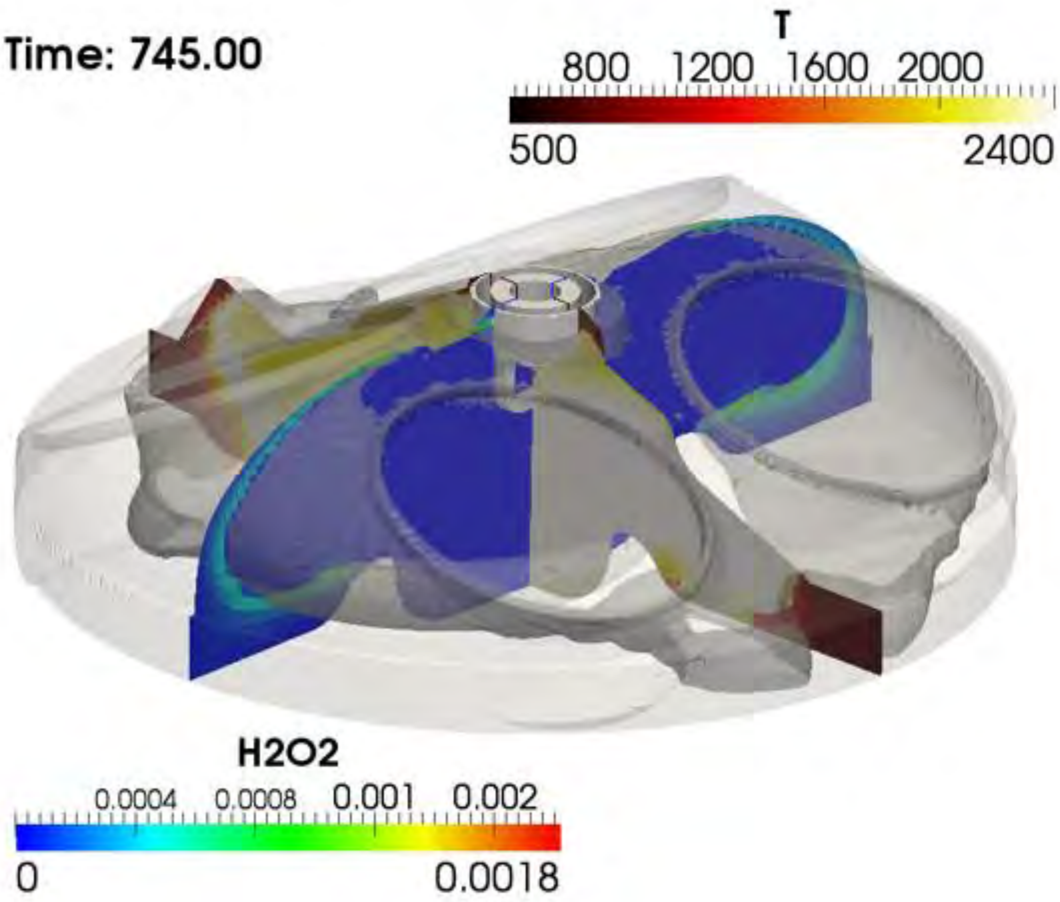
$$\frac{\partial \rho \Sigma}{\partial t} + \frac{\partial \rho u_i \Sigma}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\frac{\mu}{Sc} + \frac{\mu_t}{Sc_t} \right) \frac{\partial \Sigma}{\partial x_i} \right] + P \cdot \Sigma - D \cdot \Sigma + P_k$$

Possibility to choose different expressions for P and D depending on the selected FSD approach.

Turbocharged GDI engine

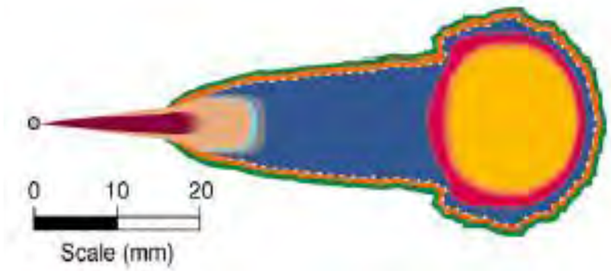
Coherent Flamelet Model (CFM), flame surface density transport equation.

Kinetic Mechanism: Jia et al. (reduced) for I-C_8H_{18} , 37 species, 59 reactions



Diesel combustion

Objective: to describe **auto-ignition** and **mixing controlled combustion** under different modes (conventional, multiple injections, HCCI, PCCI) using **realistic kinetic mechanisms** and accounting for **turbulence-chemistry interaction**.



Well-mixed model

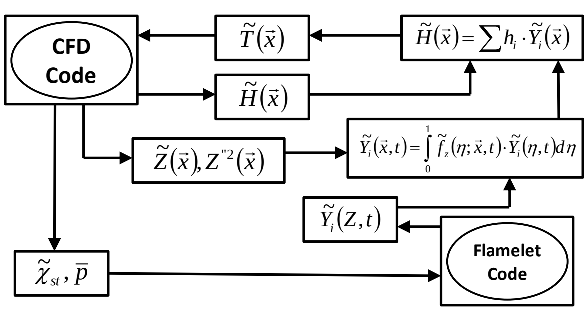
- Each cell is a well-stirred reactor
- ODE stiff solver computes reaction rates

$$Y_i^*(t+\Delta t) = Y_i(t) + \int_t^{t+\Delta t} \dot{\omega}_i \frac{W_i}{\rho} dt'$$

$$\dot{Y}_i = \frac{Y_i^*(t+\Delta t) - Y_i(t)}{\Delta t}$$

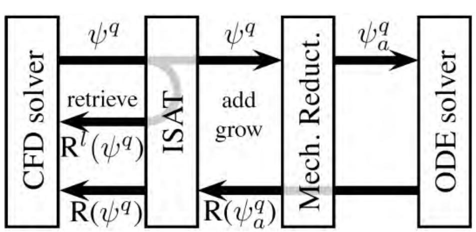
MRIF model

- Diesel flame is an ensemble of multiple unsteady diffusive flamelets

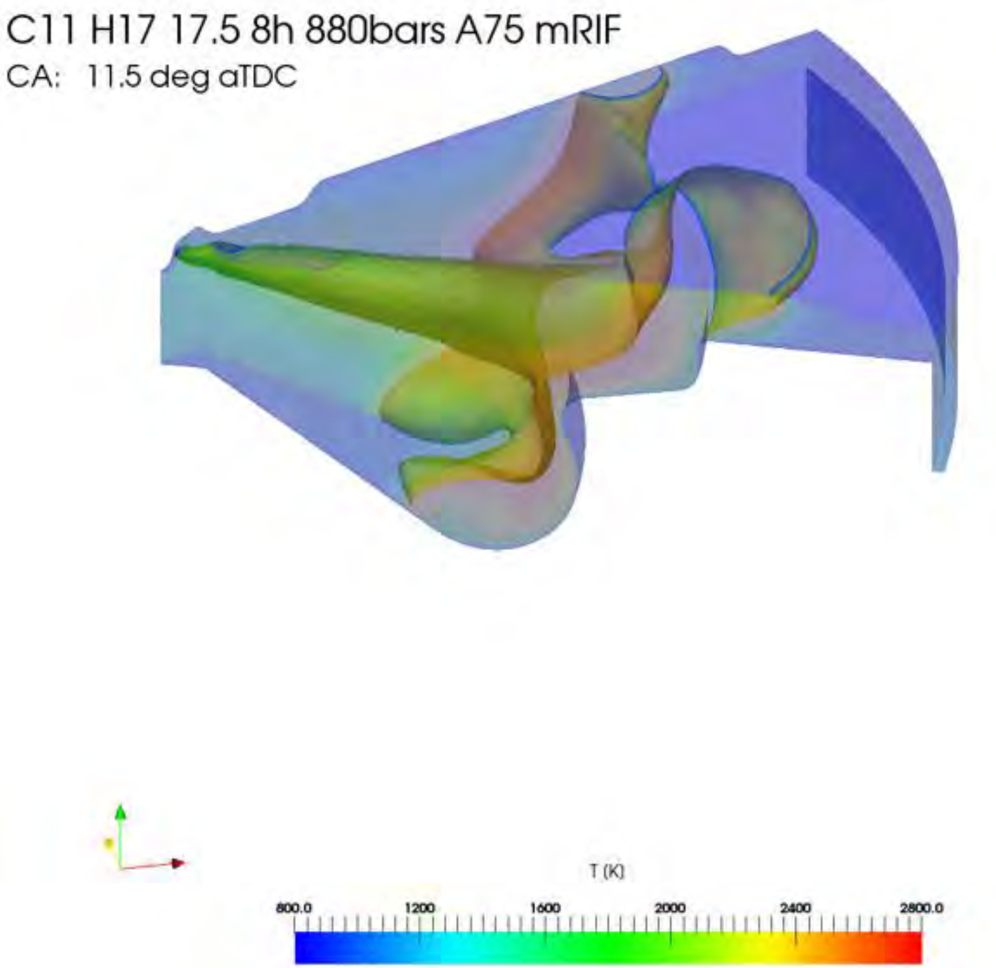


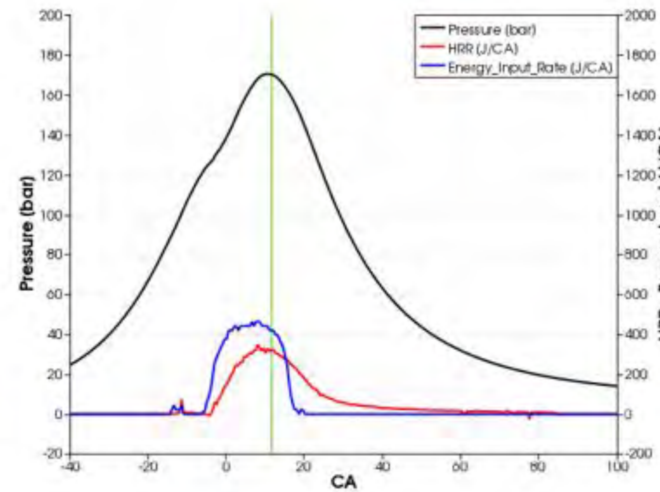
TDAC

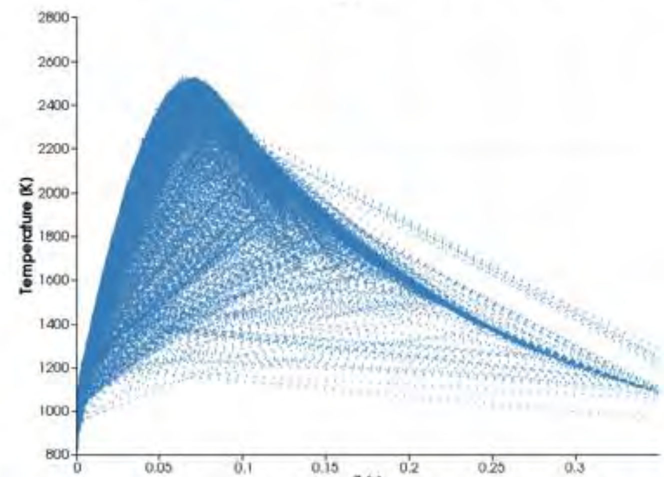
- On-line tabulation and mechanism reduction techniques to reduce the CPU time



HD engine operating point: mRIF model





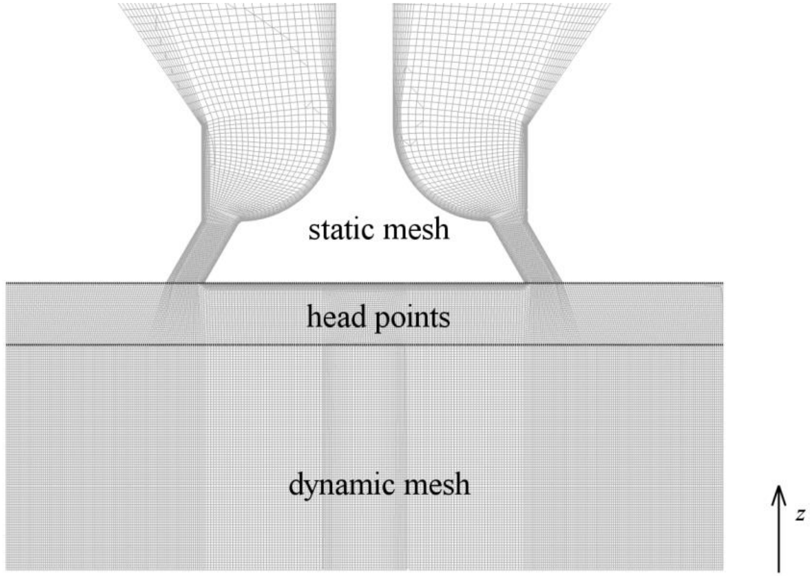


This work was sponsored and carried out in collaboration with FPT – Arbon (CH)

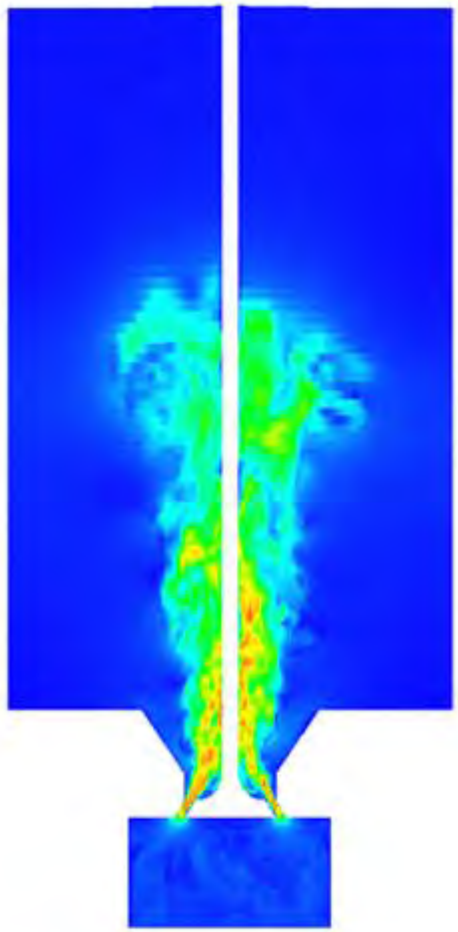
Acknowledgments: Dr. Gilles Hardy

LES of cylinder-like geometries

Subgrid scale (SGS) models implemented in OpenFOAM/Lib-ICE: dynamic Smagorinsky, Whale, Sigma, …

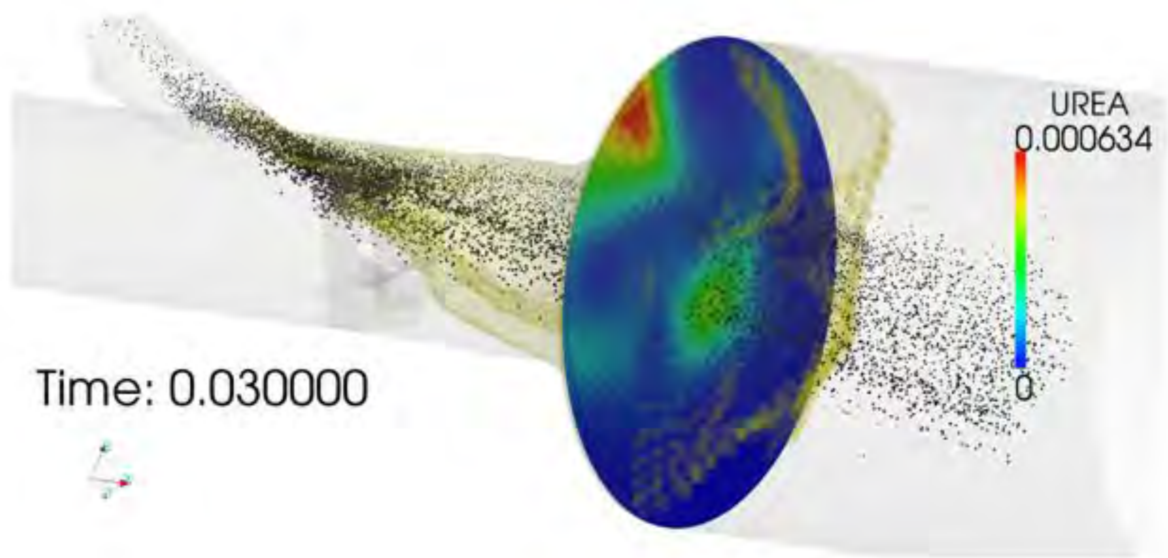


Grid used for the simulations:
4.8 million hexahedral elements, including the plenum.



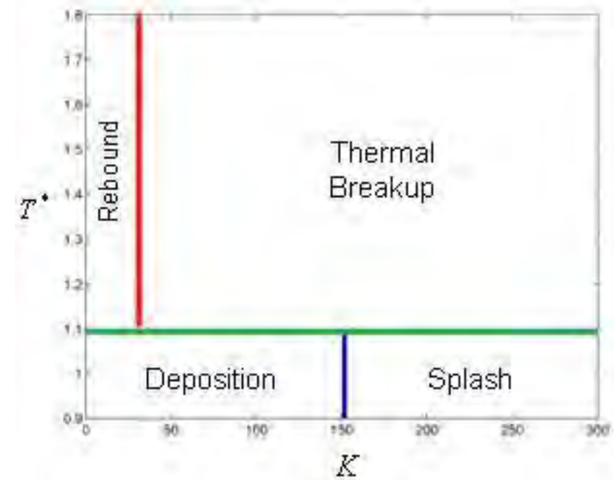
After-treatment: SCR

- Unsteady flow solver with Lagrangian tracking of particles.
- Multi-component liquid mixture and homogeneous chemical reactions (Urea thermal decomposition).
- Wall film formation and evaporation.

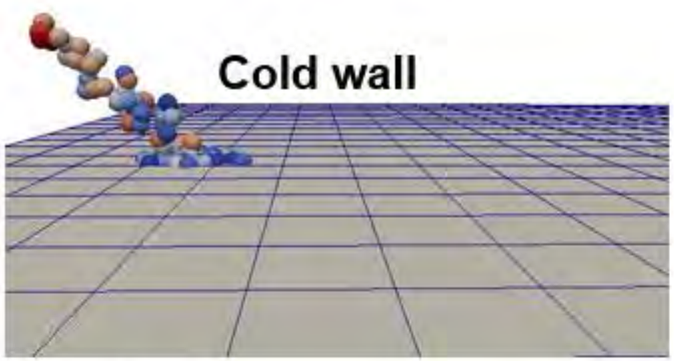


SCR modeling: injection of AdBlue

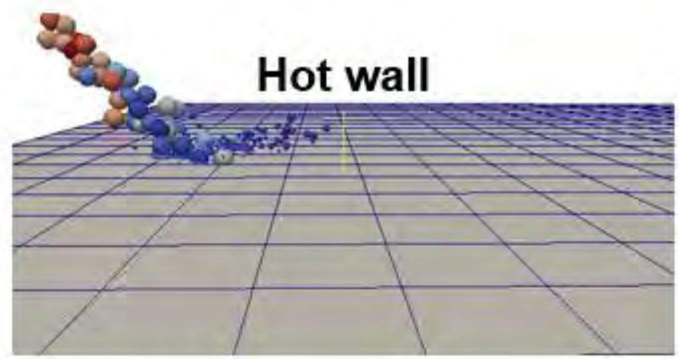
- Multi-component liquid mixture customized properties for Urea along with multi-component liquid film.
- Temperature dependence of the spray-wall interaction and wall cooling effect.



Absolute We = 264
Normal We = 137



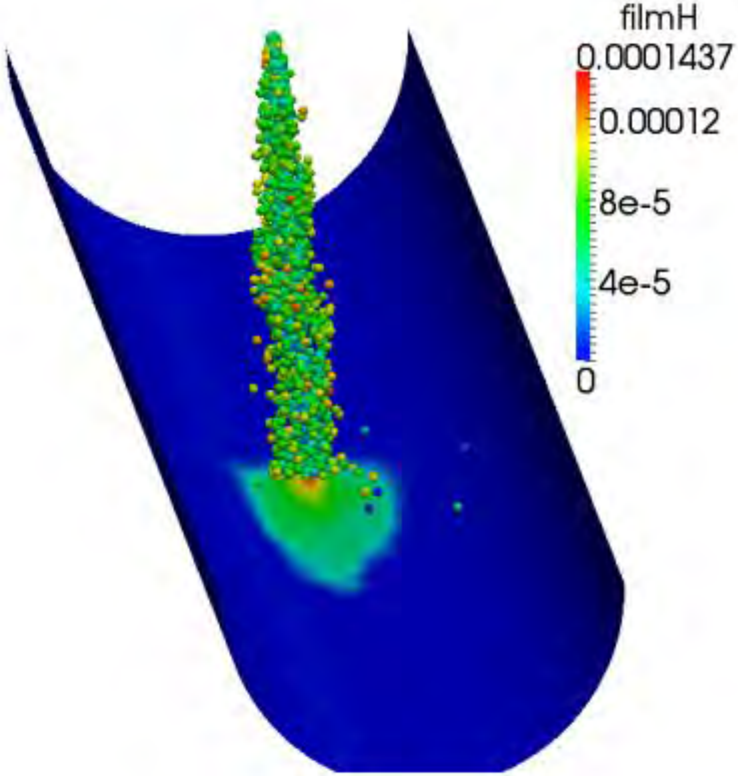
T* = 0.8



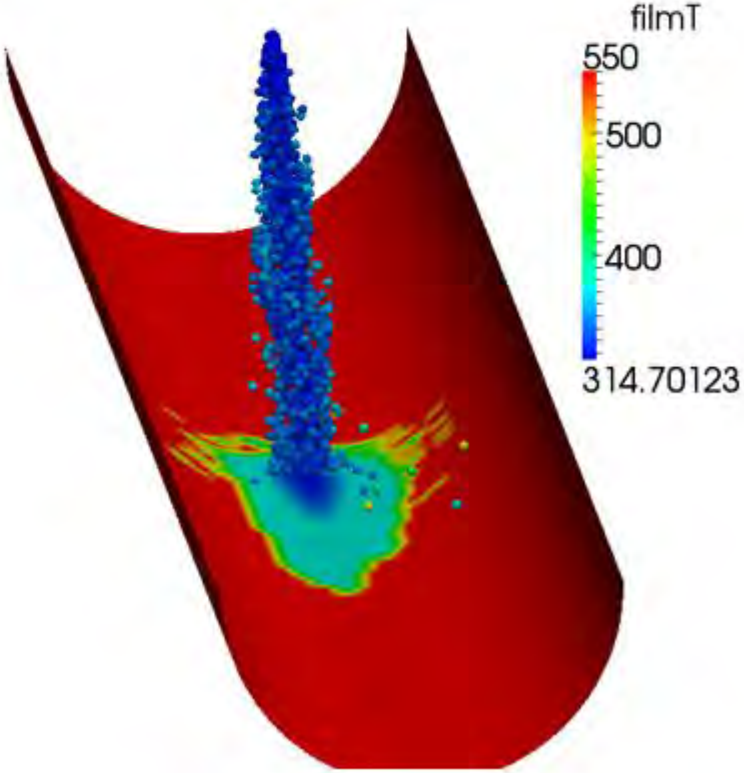
T* = 1.2

SCR: wall film modeling

Film thickness

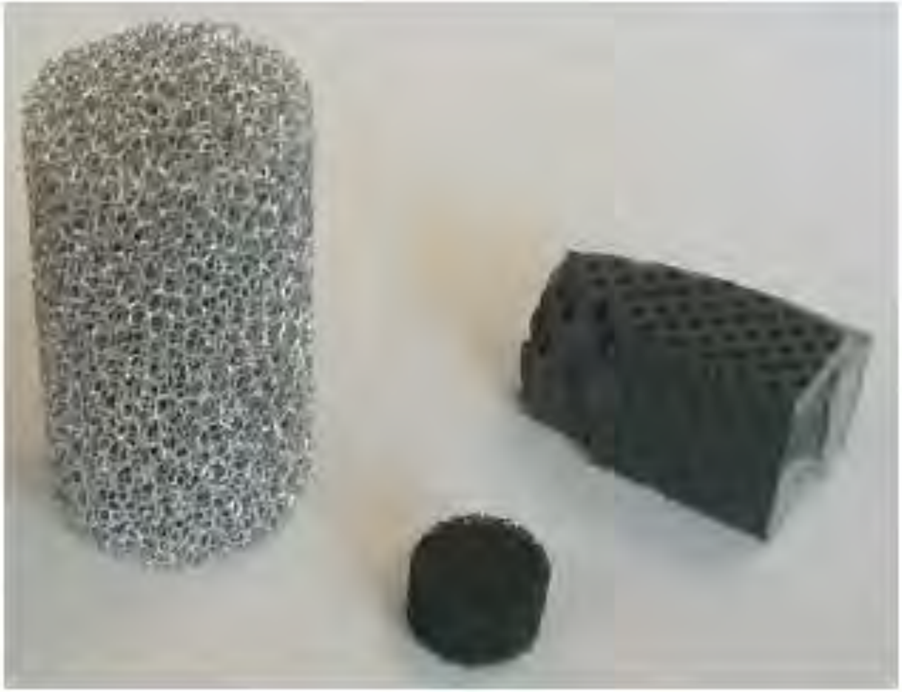


Film temperature



After-treatment: open-cell foams

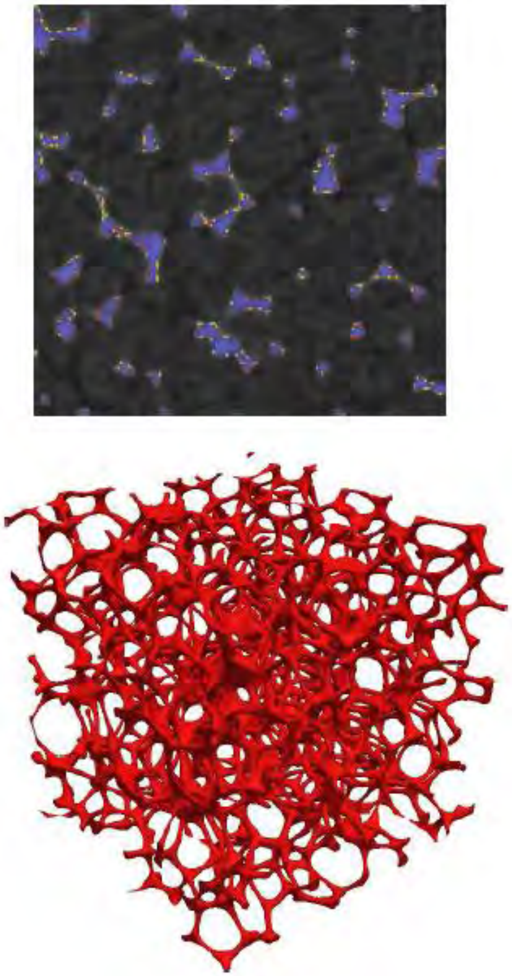
CFD simulation of open-cell foams



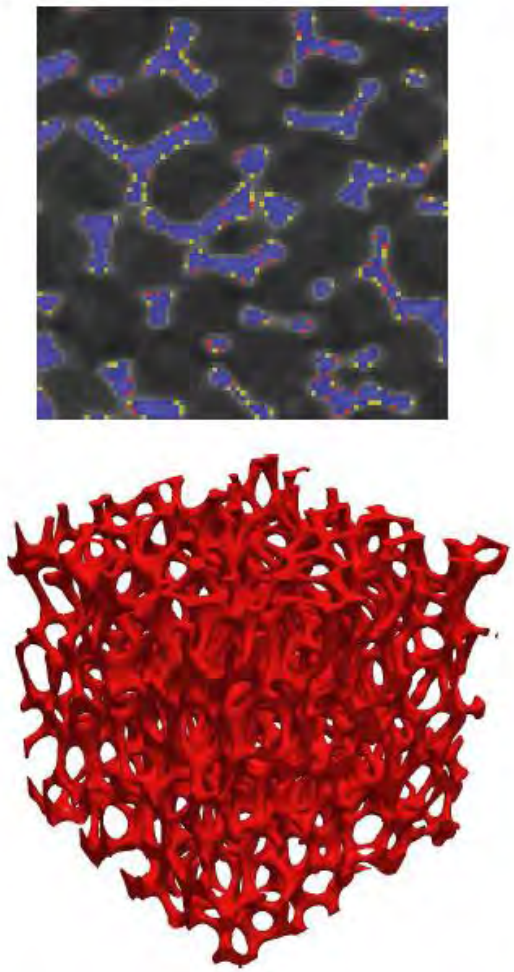
Foam samples

Micro-CT: image processing

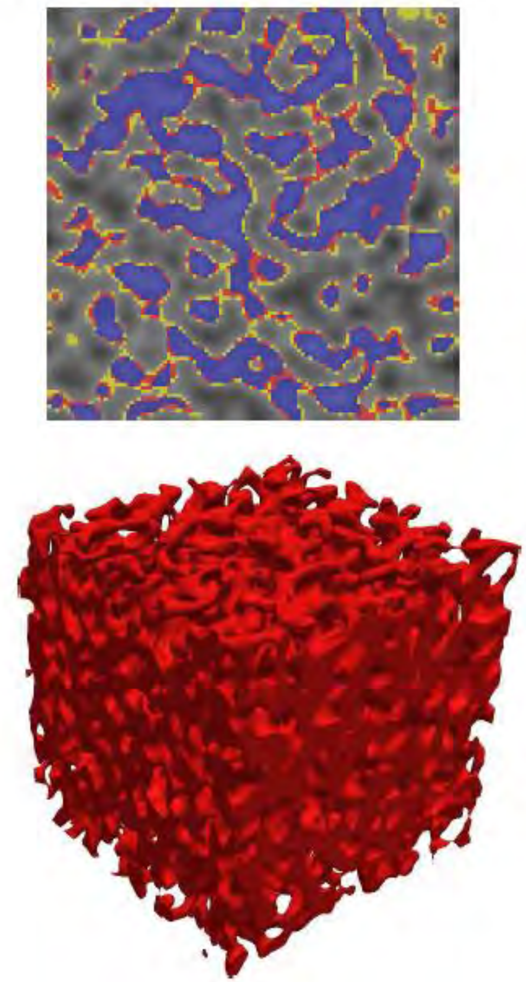
Al foam
porosity: 95-97%



SiC foam
porosity: 85-90%

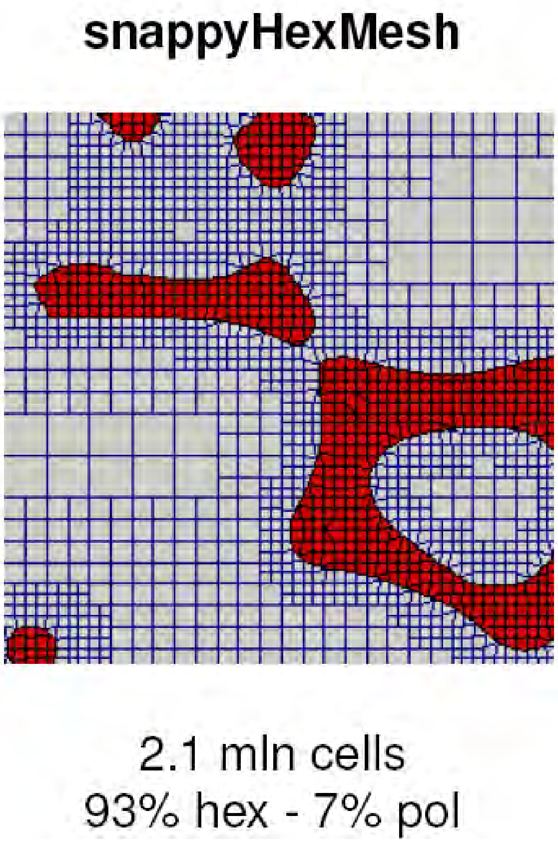


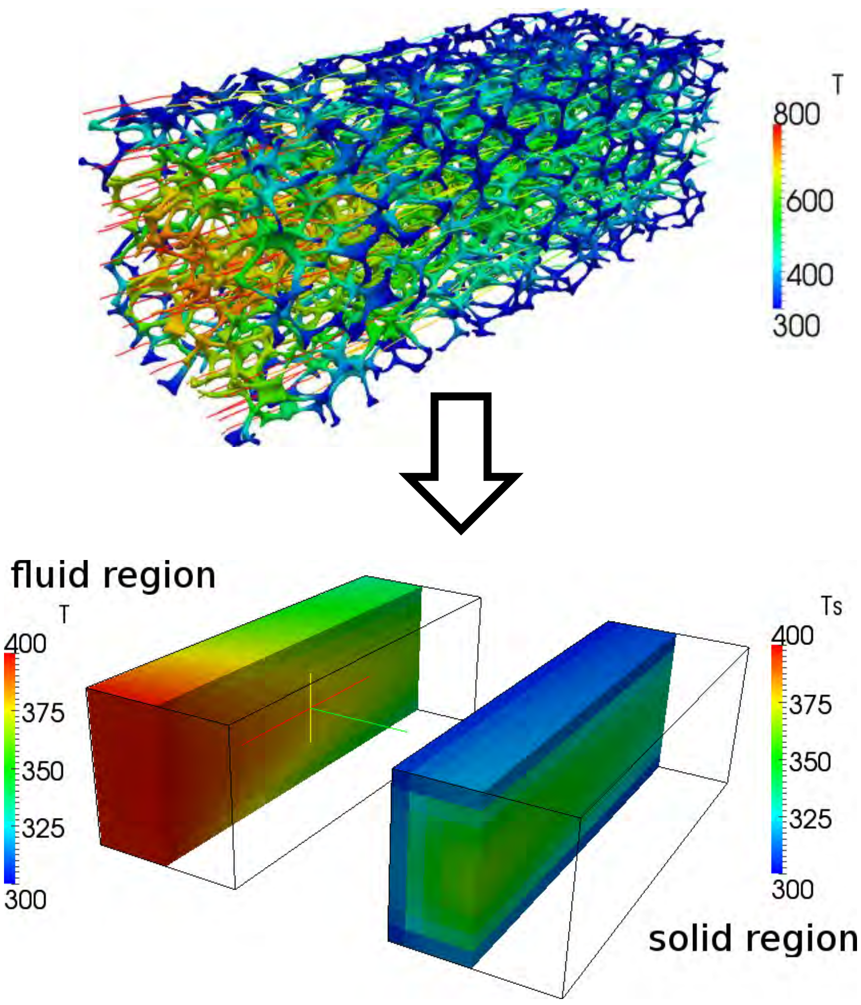
Cordierite
porosity: 45-55%



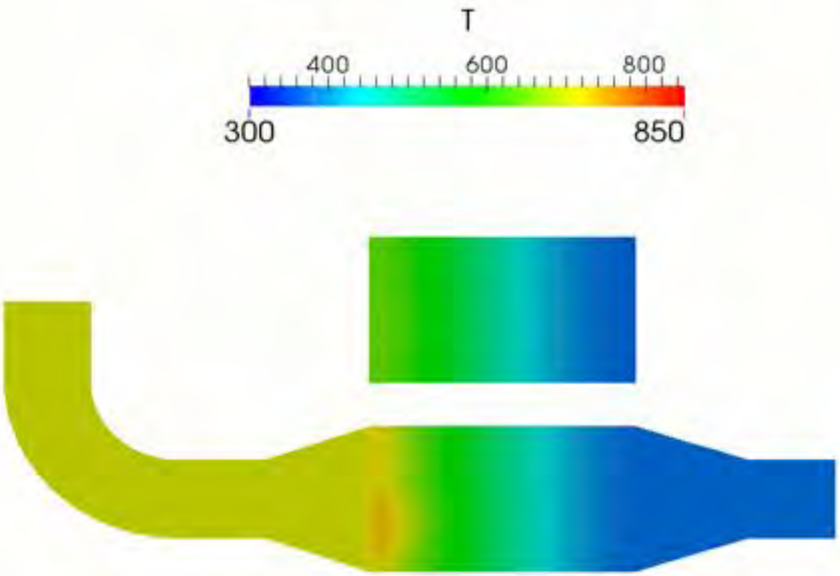
Reacting flows in porous media

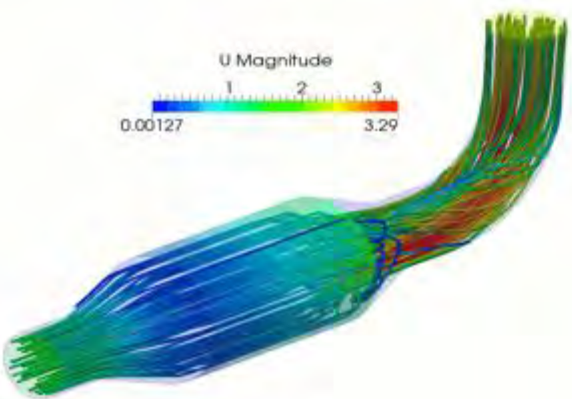
From micro-scale to full scale simulation of after-treatment systems:





Application example: TWC





CO oxidation

$CO + 0.5O_2 \rightarrow CO_2$

H_2 oxidation

$H_2 + 0.5O_2 \rightarrow H_2O$

HC oxidation

$C_3H_6 + 3O_2 \rightarrow 3CO_2 + 6H_2O$

NO_x reduction

$CO + NO \rightarrow CO_2 + 0.5N_2$

$H_2 + NO \rightarrow H_2O + 0.5N_2$

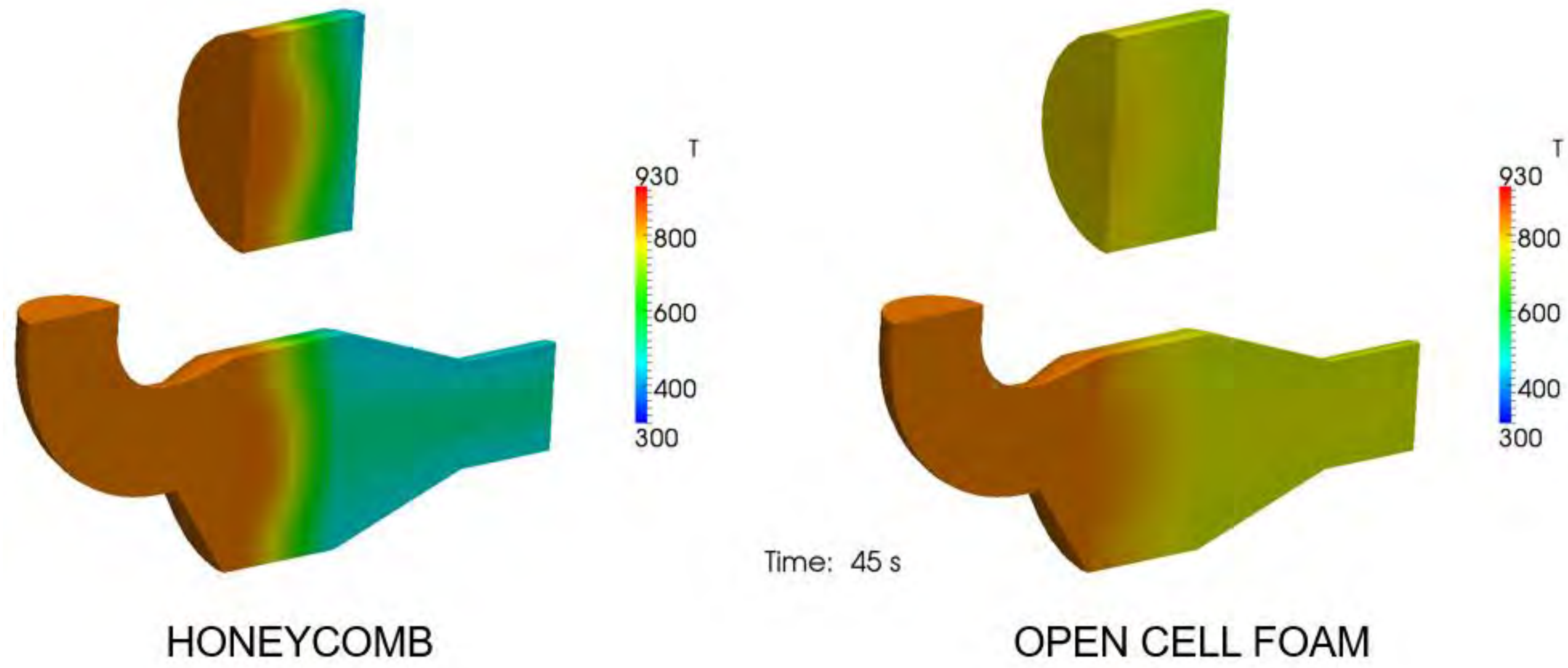
Steam water reforming

$CO + H_2O \rightarrow CO_2 + H_2$

$C_3H_6 + 3H_2O \rightarrow 3CO_2 + 6H_2$

Full scale: honeycomb vs open cell foam

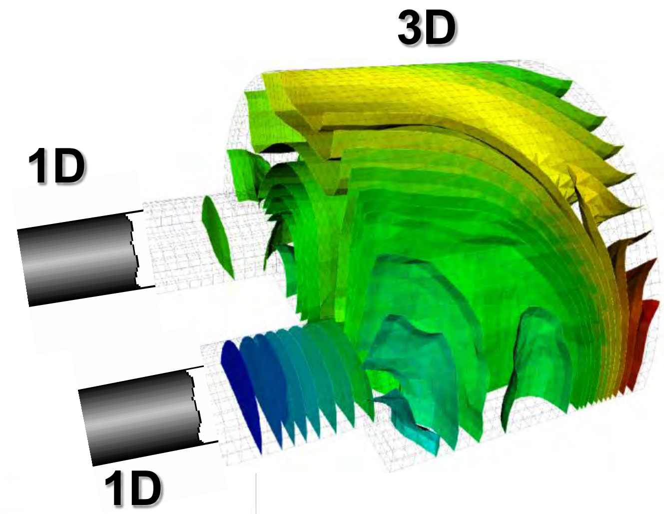
NEDC cycle of a 2.0 L engine (4 Cyl, naturally aspirated) simulated imposing the measured exhaust gas T and mass flow ad the engine flange.

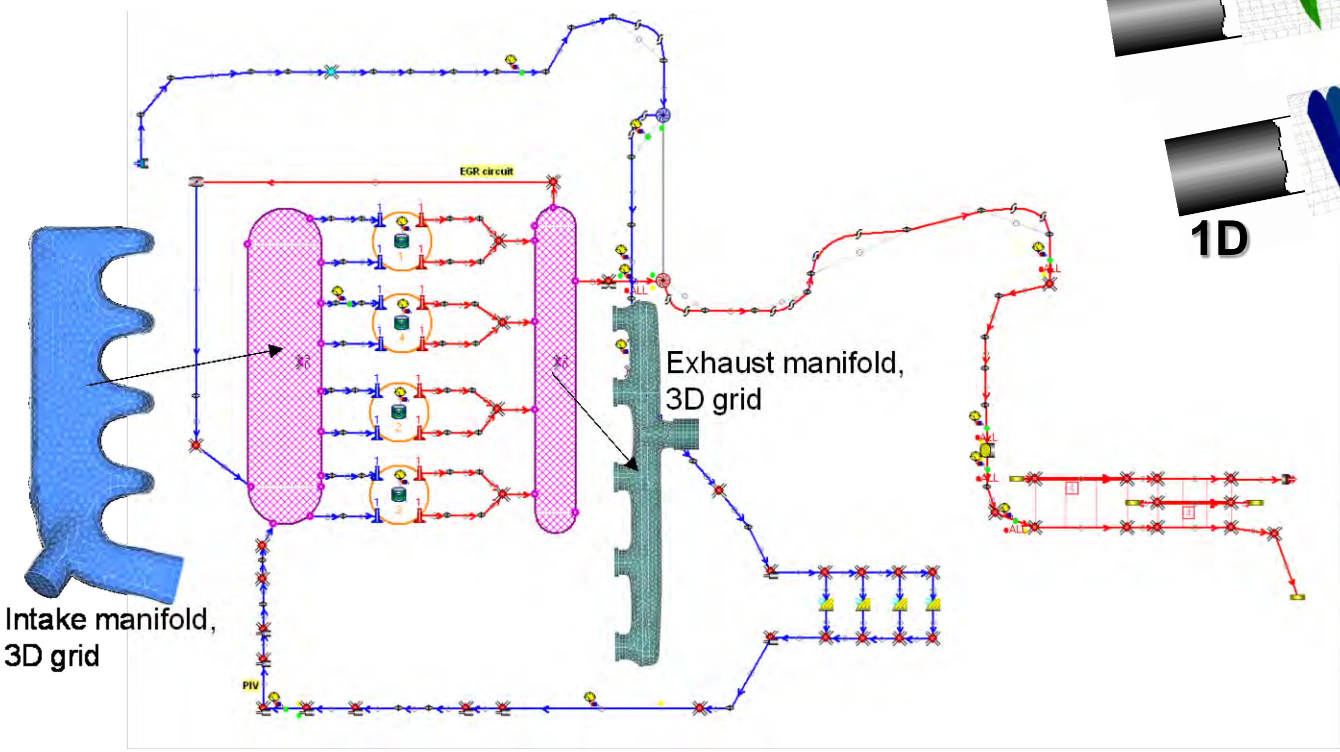


Coupled 1D-3D simulations

Unsteady flows in intake and exhaust systems:

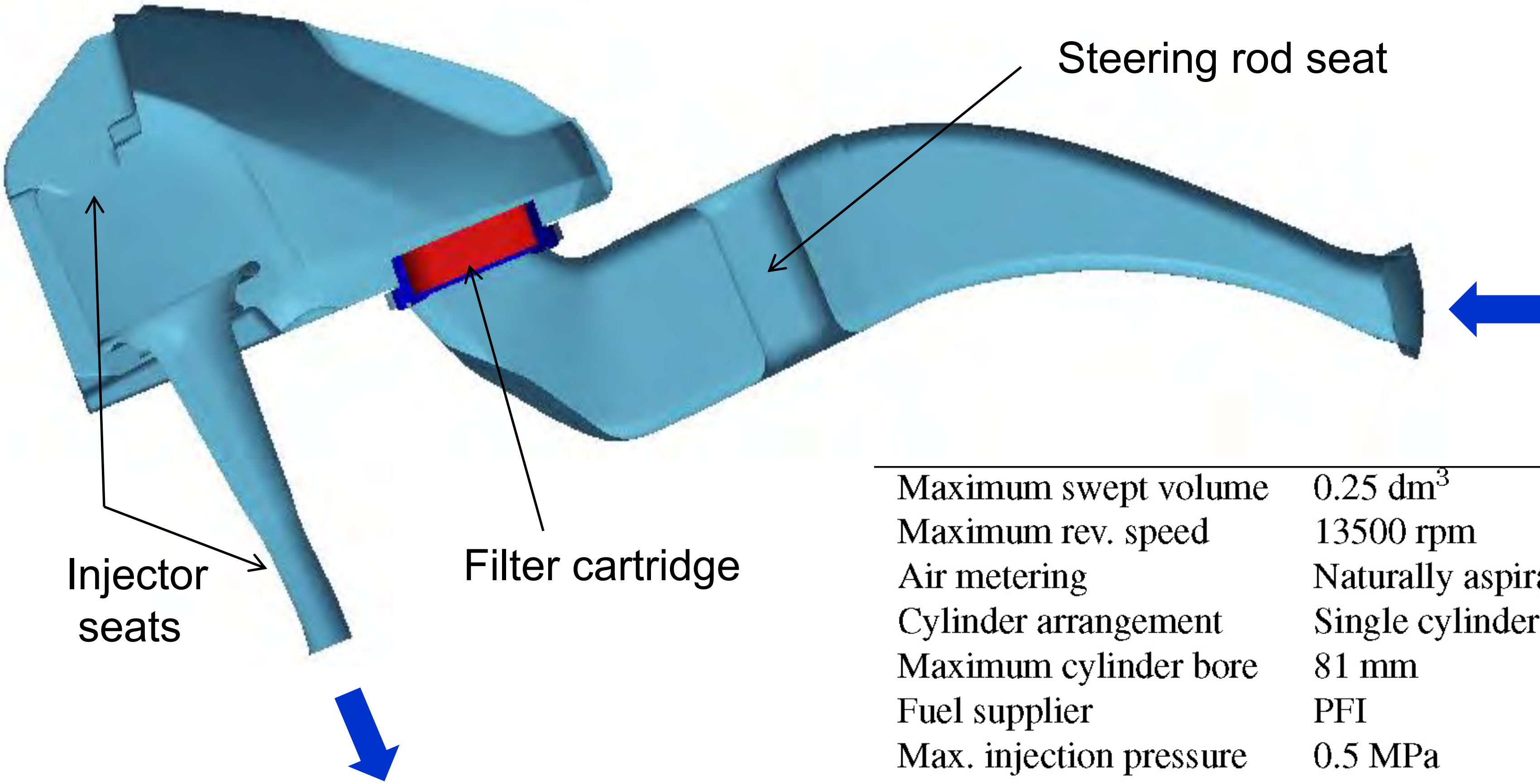
1D-3D coupling





1D-3D schematic of a single cylinder engine

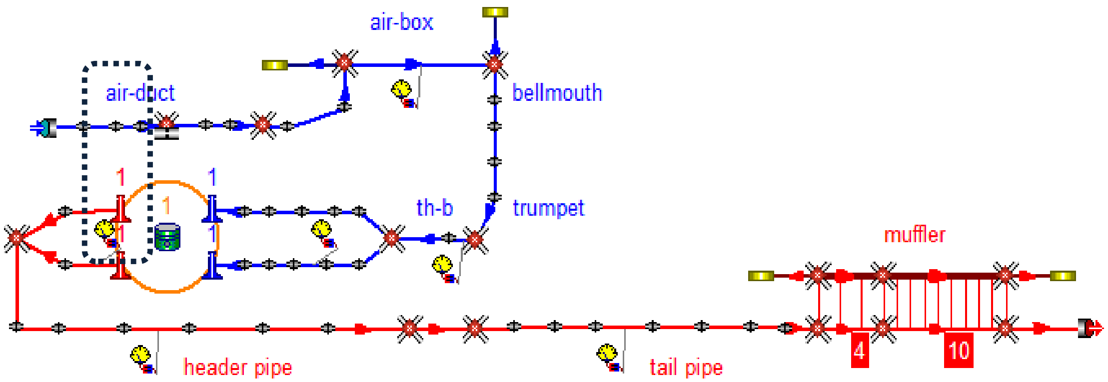
MOTO3, Mahindra racing

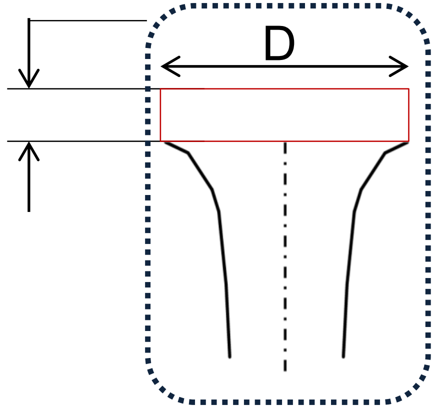


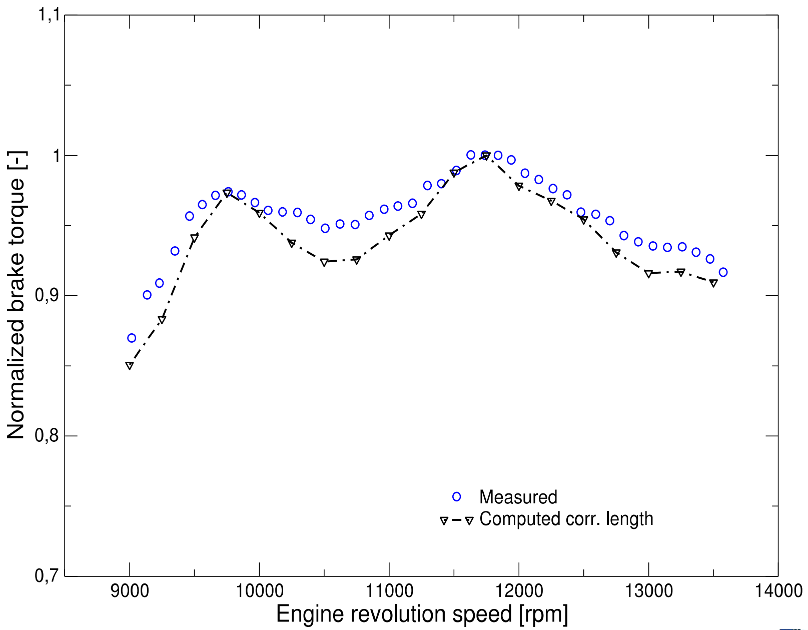
Maximum swept volume	0.25 dm^3
Maximum rev. speed	13500 rpm
Air metering	Naturally aspirated
Cylinder arrangement	Single cylinder
Maximum cylinder bore	81 mm
Fuel supplier	PFI
Max. injection pressure	0.5 MPa

Baseline 1D model

1D engine schematic and brake torque comparison



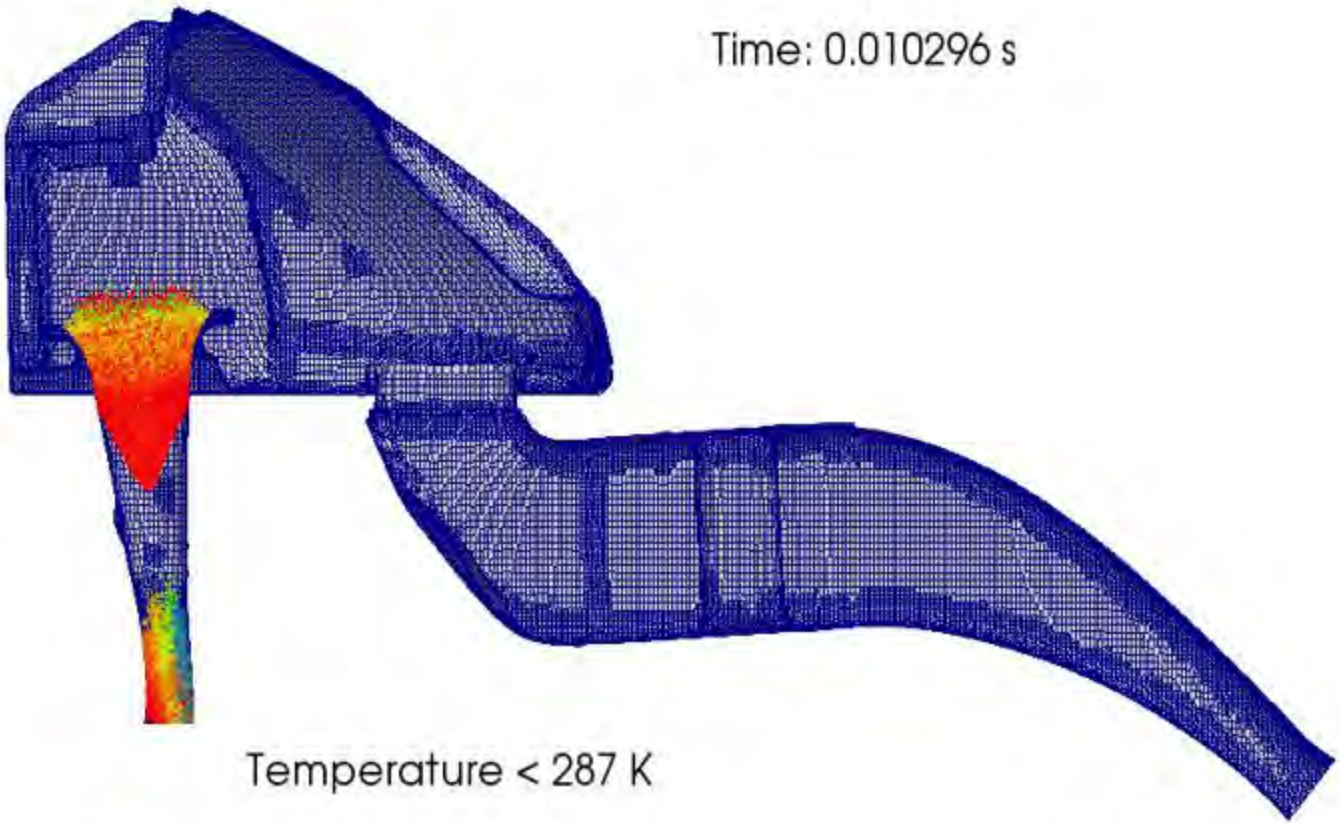




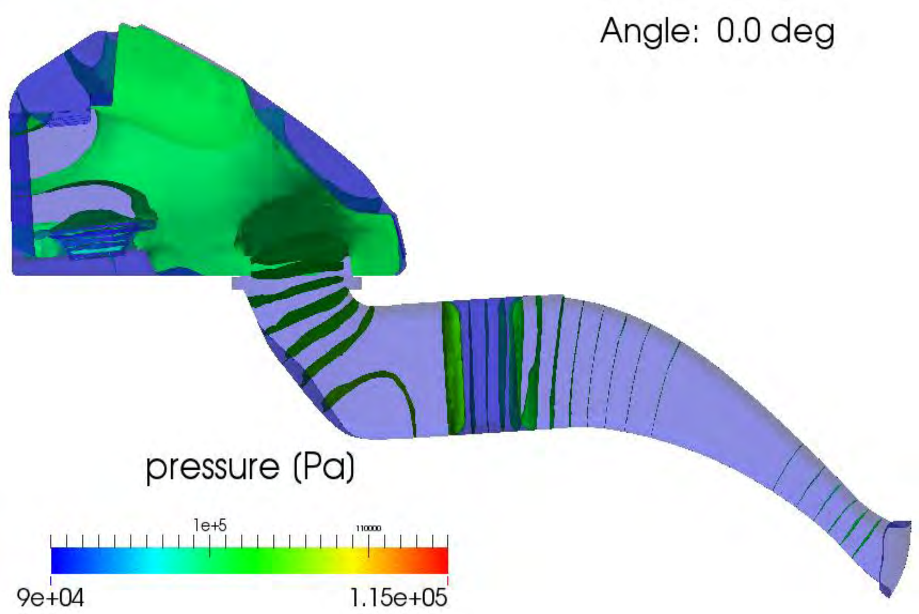
GROUP
POLITECNICO DI MILANO

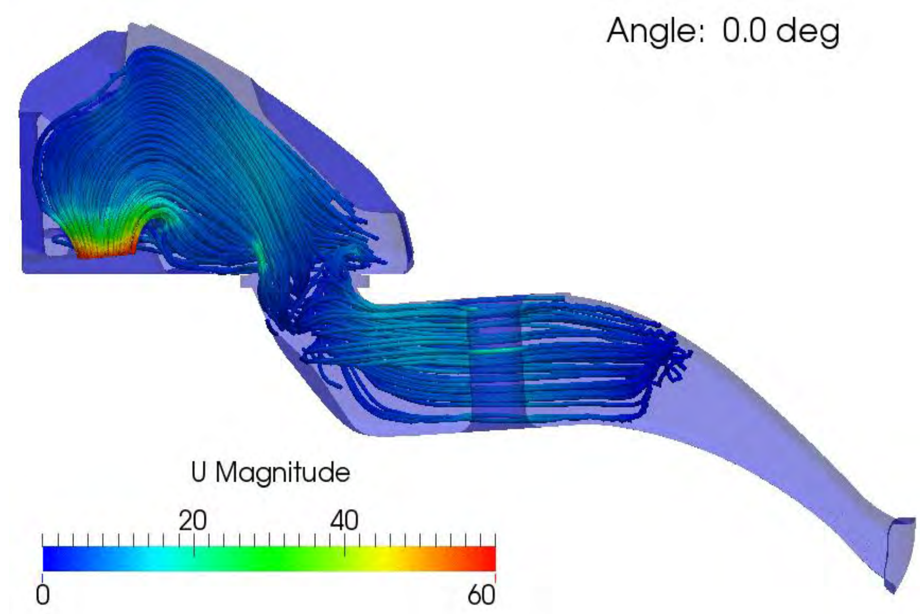
Modeling the effect of spray evaporation

Gasoline injection: lower and upper injectors



Pressure and velocity fields

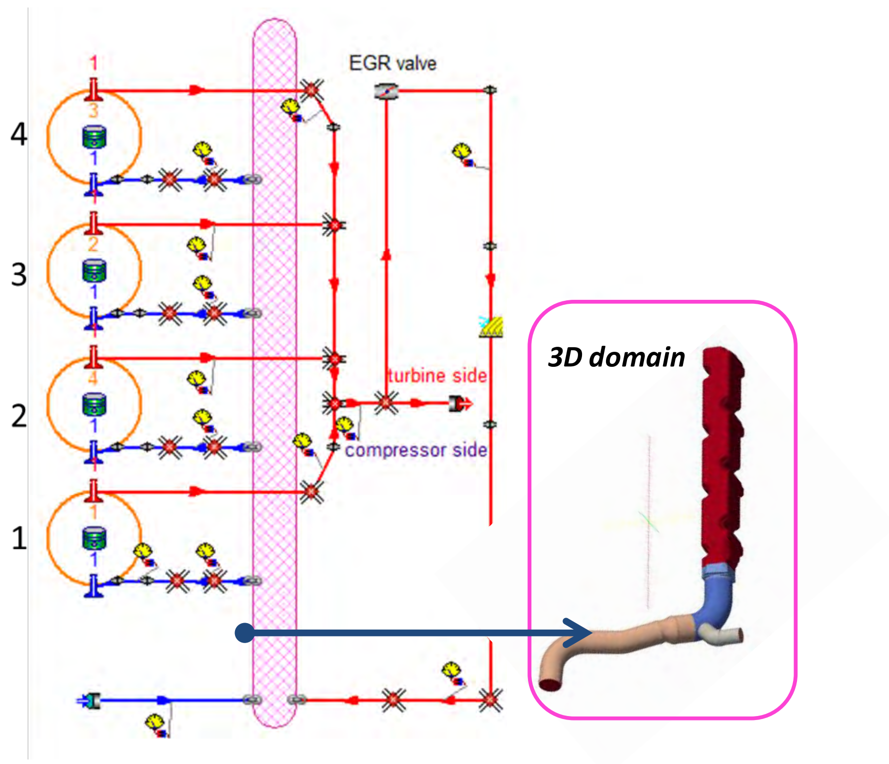


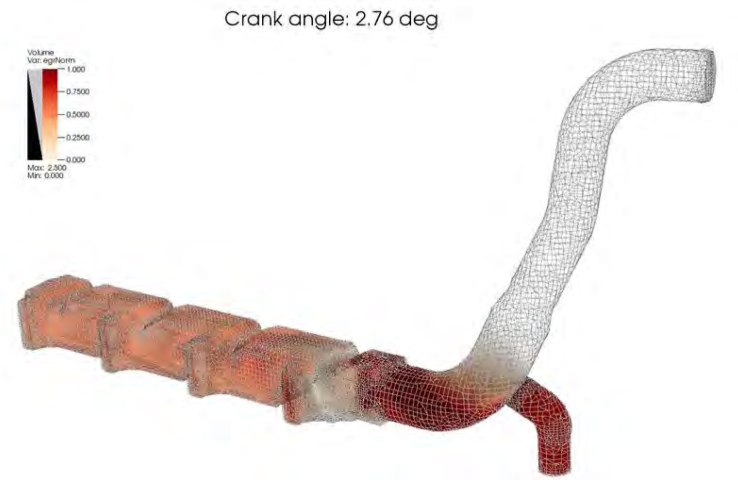


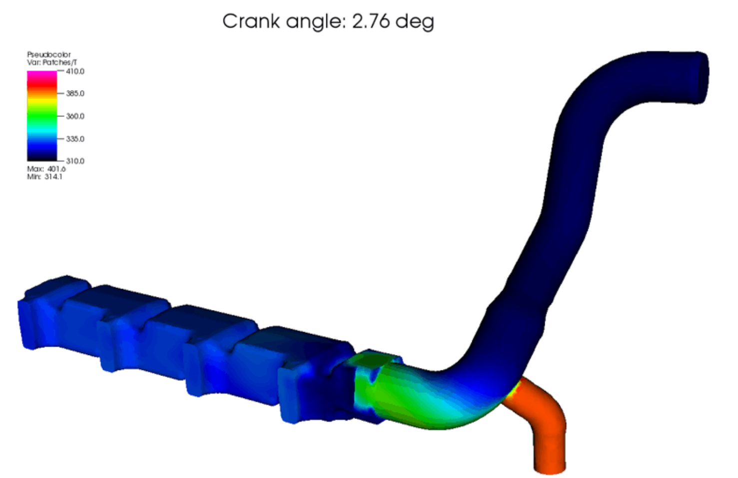
- Visible resonance excited by longitudinal characteristic length.
- Steering rod seat gives some dynamic effects (pressure reflections) and steady state losses (pressure losses due to average flow).
- Intake pipe shows planar wave behaviour.

Simulation of EGR systems (1D-3D coupling)

4-cylinder Diesel engine for agricultural applications: full torque conditions with EGR



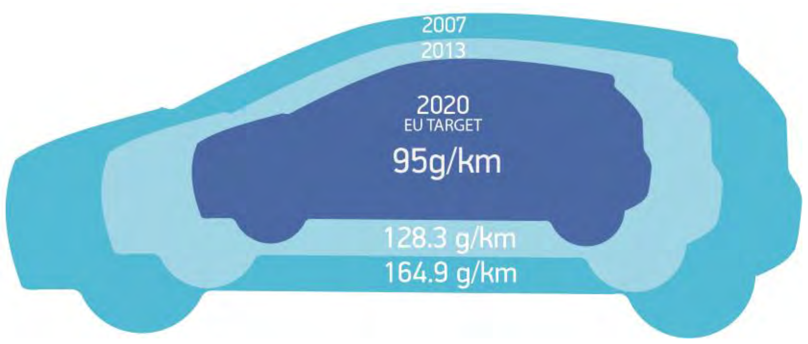




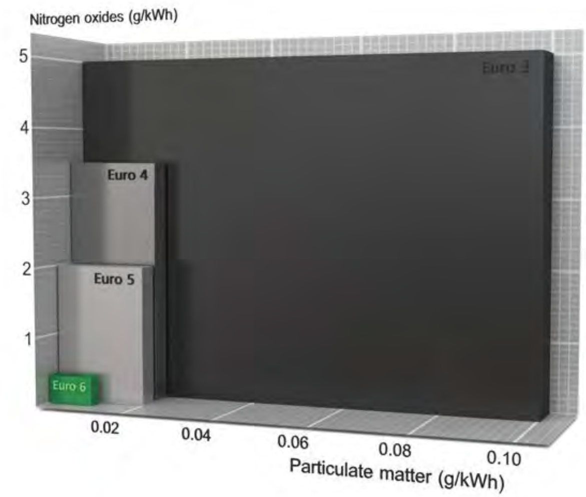
Conclusions

Internal combustion engine development will never stop!

Efficiency increase



Pollutant emission control



Conclusions

Internal combustion engine development will never stop!

Research work will be required for the next generation of 1D and 3D CFD simulation models…