1D-3D COUPLED SIMULATION OF THE FUEL INJECTION INSIDE A HIGH PERFORMANCE ENGINE FOR MOTORSPORT APPLICATION: SPRAY TARGETING AND INJECTION TIMING

M. Fiocco, D. Borghesi- Mahindra Racing S.P.A.

Outline

- Introduction and motivation
- Level of approximation
  - 1D approach
  - 3D model for spray and wall film
  - 1D-3D coupling

- Application to a racing motorbike engine
  - 1D strategy and model calibration
  - 1D-3D simulation

- Analysis of the spray-gas interaction: timing and targeting
- Optimized configurations
- Conclusions

Motivation

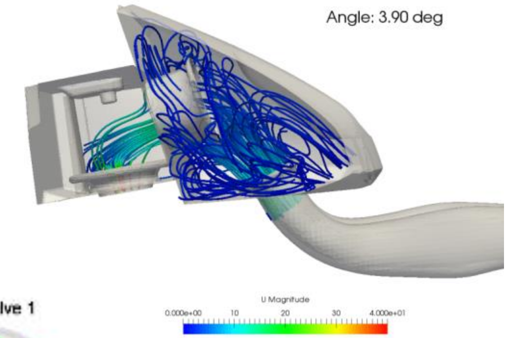
Research collaboration between Politecnico di Milano and Mahindra Racing

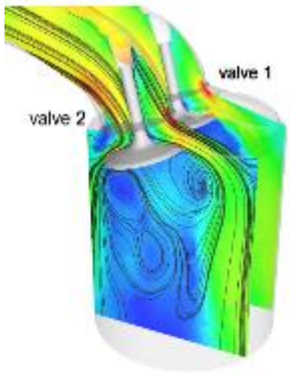
- Computational fluid-dynamic studies of the engine induction system for a competition motorbike

- Goals
  - Understanding
    - air-box behavior
    - air-fuel spray interaction
  - Improving
    - Performance
    - Engine response during transients

Introduction

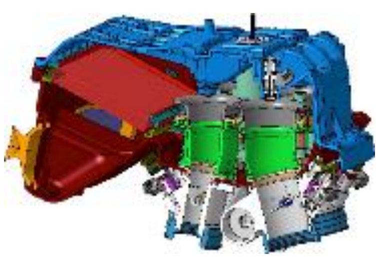
- 1D tools are widely used for the modeling of the complete engine configuration, where intake and exhaust systems are coupled to the engine:
  - Flexible
  - Reliable
  - Short computation time





- The intake systems plays different roles:
  - Wave action optimization
  - **Air fuel mixture preparation**
  - Air filtering

- 1D models are limited in predicting such process when physics and shape become complex



- 3D or 1D-3D coupled simulations may become useful

1D governing equations

1D thermo-fluid dynamic code GASDYN

- The numerical model is based on the conservation equations for one-dimensional, unsteady, compressible, reacting flows in ducts with variable cross-section

$$\frac{\partial(\rho F)}{\partial t} + \frac{\partial(\rho u F)}{\partial x} = 0$$

$$\frac{\partial(\rho u F)}{\partial t} + \frac{\partial\left(\rho u^2 F + pF\right)}{\partial x} = p\frac{\partial F}{\partial x} - \frac{2}{D}\rho u|u| f_w F$$

$$\frac{\partial(\rho e_0 F)}{\partial t} + \frac{\partial(\rho e_0 u F + upF)}{\partial x} = \rho q F.$$

$$\frac{\partial \mathbf{W}(x,t)}{\partial t} + \frac{\partial \mathbf{F}(\mathbf{W})}{\partial x} + \mathbf{B}(\mathbf{W}) + \mathbf{C}(\mathbf{W}) = 0$$

$$\mathbf{W}(x,t) = \begin{bmatrix} \rho F \\ \rho u F \\ \rho e_0 F \\ \rho \mathbf{Y} F \end{bmatrix}, \quad \mathbf{F}(\mathbf{W}) = \begin{bmatrix} \rho u F \\ \rho u^2 F + pF \\ \rho u h_0 F \\ \rho u \mathbf{Y} F \end{bmatrix}, \qquad \mathbf{B}(\mathbf{W}) = \begin{bmatrix} 0 \\ -p\dfrac{dF}{dx} \\ 0 \\ 0 \end{bmatrix}, \quad \mathbf{C}(\mathbf{W}) = \begin{bmatrix} 0 \\ \rho G F \\ -\rho(q + q_{re})F \\ -\rho \dot{\mathbf{Y}} F \end{bmatrix},$$

- Symmetric FD/FV methods with second order accuracy (the two-step Lax-Wendroff of the WAF method) with the addition of flux-limiting techniques

3D conservation equations: Navier-Stokes

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- Conservation equations of mass, momentum and energy for a compressible Newtonian fluid.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = S p_p$$

$$\frac{\partial (\rho \mathbf{U})}{\partial t} + \nabla \cdot \left(\rho \mathbf{U}\mathbf{U} + p \bar{\bar{\mathbf{I}}} - \bar{\bar{\tau}} \right) = \rho \mathbf{f}_e + S u_p$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho H \mathbf{U} - k \nabla T - \bar{\bar{\tau}} \cdot \mathbf{U}) = \rho \mathbf{f}_e \cdot \mathbf{U} + S h_p$$

- Closure equations: equation of state and the turbulence model (standard k-epsilon)
- Terms to couple mass, momentum and energy equations for the gas phase with the liquid spray

Lagrangian tracking of fuel droplets

- The spray droplets are described by Lagrangian approach on stochastic particles referred to as parcels.
- Spray-wall interaction is unavoidable
- Exchange of mass, momentum and energy between the liquid (Lagrangian) the gas (Eulerian) phase:

  - **Mass**

$$\dot{m}_d = -\pi D \Gamma \rho_v Sh \ln \left(1 + \frac{X_{v,s} - X_{v,\infty}}{1 - X_{v,s}} \right)$$

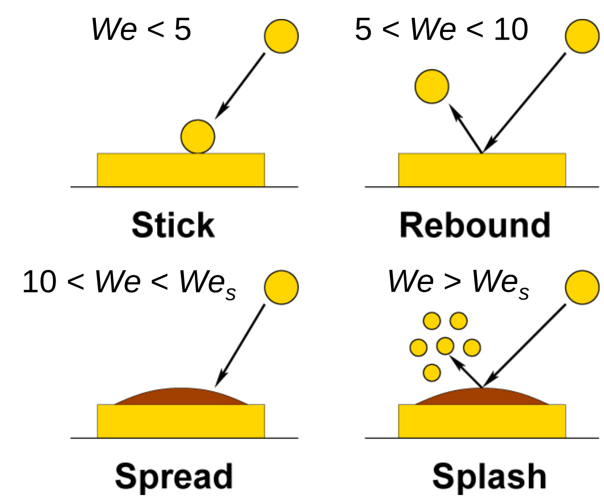
  - **Momentum**

$$\mathbf{F} = -\frac{\pi D^2}{8} \rho C_D \left| \mathbf{U}_d - \mathbf{U} \right| \left(\mathbf{U}_d - \mathbf{U} \right)$$

  - **Energy**

$$m_d \frac{dh_d}{dt} = \dot{m}_d h_v(T_d) + \pi D \kappa Nu (T - T_d) f$$

$$We = \frac{\rho \left(\overrightarrow{U}_P \overrightarrow{n}_w \right) d_0}{\sigma}$$



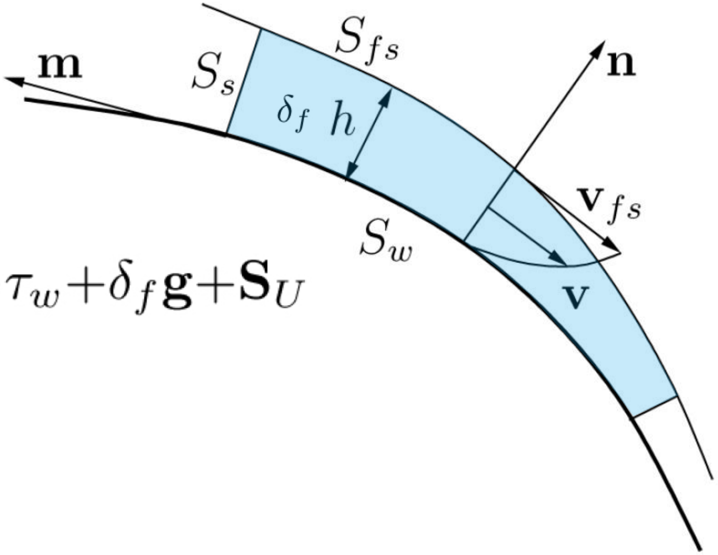
$$We_s = (18)^2 d_0 \left(\frac{\rho}{\sigma} \right)^{1/2} \left(\frac{\mu}{\rho} \right)^{1/4} f^{3/4}$$

Wall film modelling

$$\frac{\partial \delta_f}{\partial t} + \nabla \cdot (\delta_f \mathbf{U}_f) = S_m + S_v$$

$$\frac{\partial \delta_f \mathbf{U}_f}{\partial t} + \nabla \cdot (\delta_f \mathbf{U}_f \mathbf{U}_f) = -\frac{1}{\rho_f} \nabla (\delta_f p_f) + \tau_g - \tau_w + \delta_f \mathbf{g} + \mathbf{S}_U$$

$$\frac{\partial \delta_f H_{s,f}}{\partial t} + \nabla \cdot (\delta_f \mathbf{u}_f H_{s,f}) = j_g - j_w + S_H$$



- The wall heat balance is not solved
- The film-gas heat flux terms accounts for the contribution of the temperature gradient with the addition of the heat flux required by the evaporation
- heat flux due to conduction between the liquid and the pipe walls is considered (wall is at fixed temperature)

Coupling between 1D and 3D

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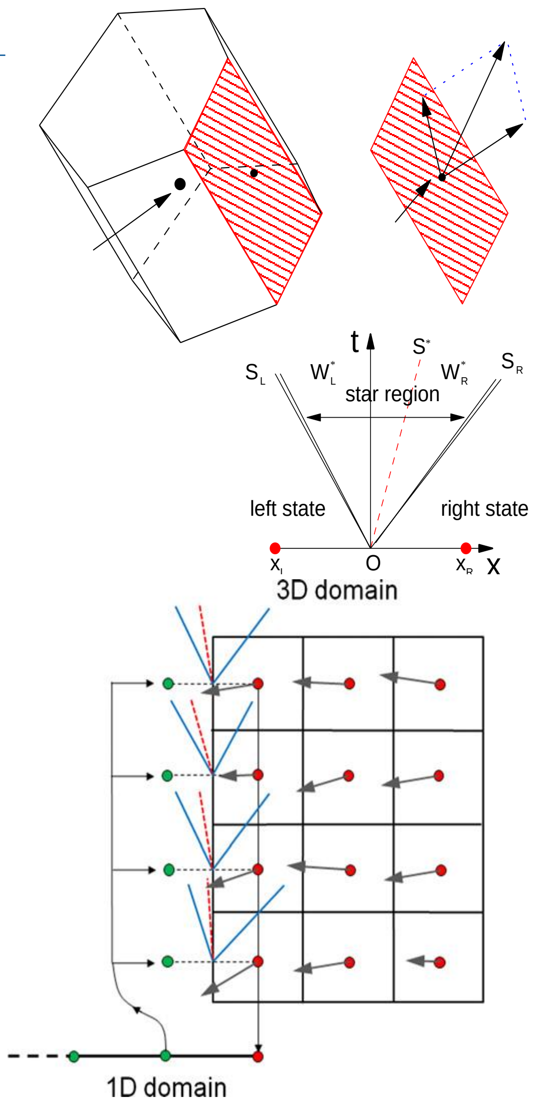
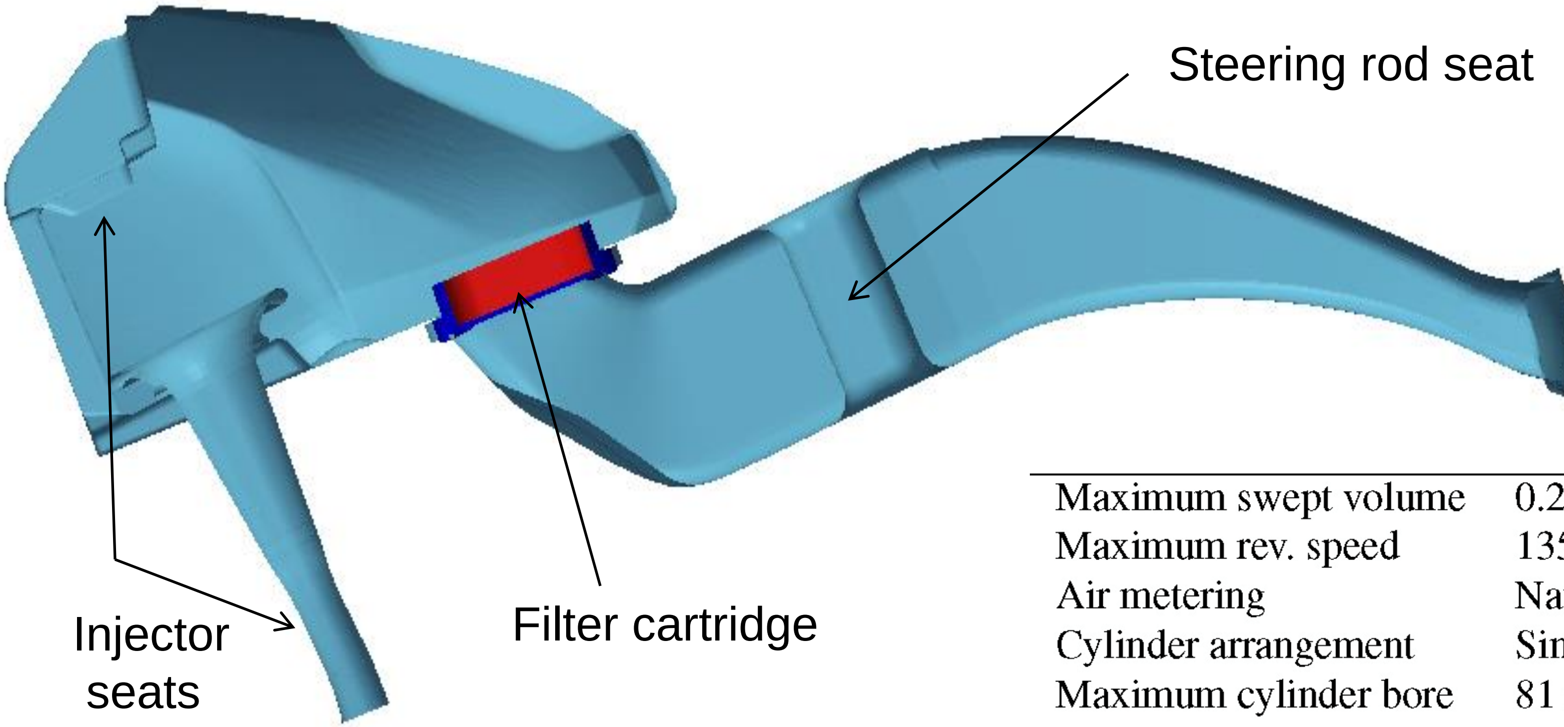
- The coupling strategy is fundamental, it must be as much flexible as possible:
  - One way
  - **Two ways**
- Usage of 1D in pipes where the 3D effects are small and the fully 3D elsewhere (for 3D wave propagation and multiphase simulation)
- Local Riemann solver solution at the interface
- Information are exchanged only for the Eulerian phase
- Lagrangian phase is not tracked inside the 1D domain
- Gas composition is not exchanged as well



Starting point MY 2016 and engine specs

State of the art of motorbike (championship 2014-2015)

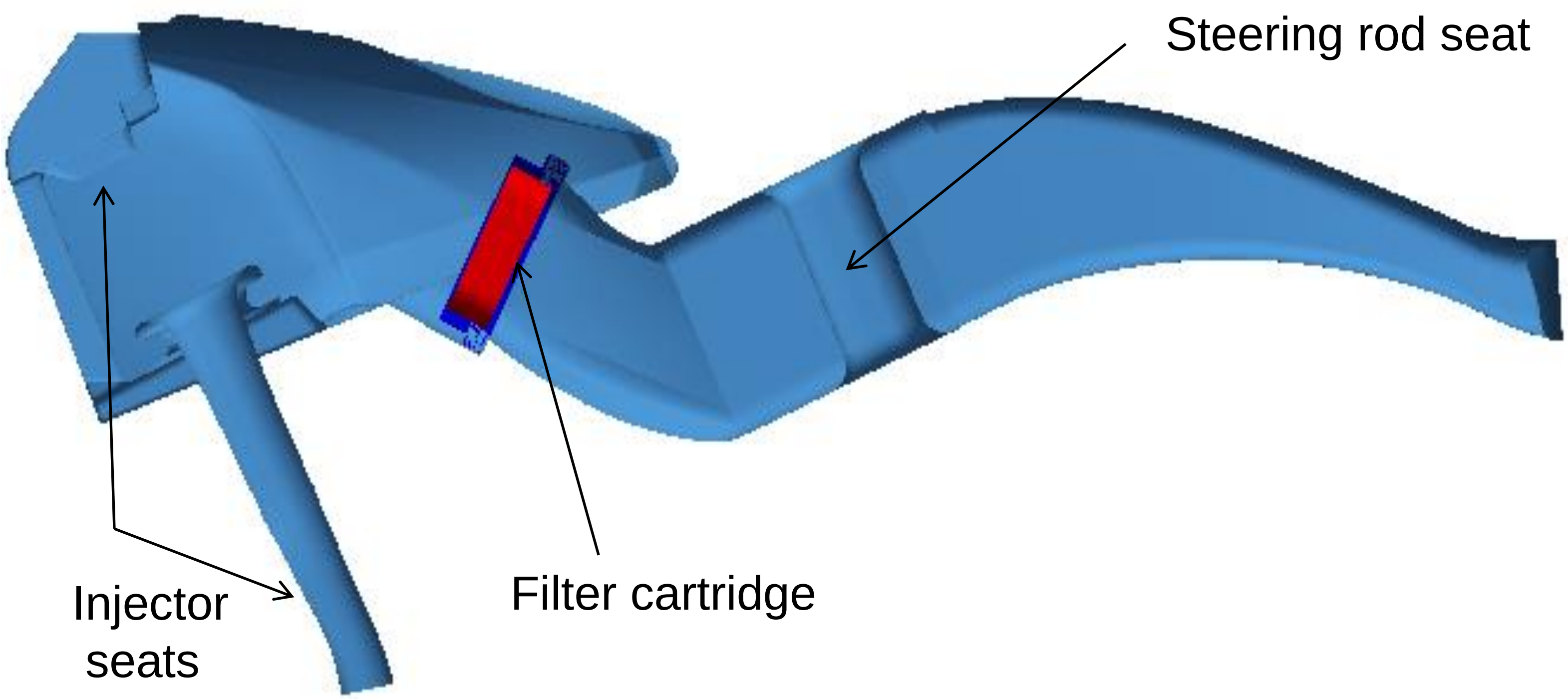


Maximum swept volume	0.25 dm^3
Maximum rev. speed	13500 rpm
Air metering	Naturally aspirated
Cylinder arrangement	Single cylinder
Maximum cylinder bore	81 mm
Fuel supplier	PFI
Max. injection pressure	0.5 MPa

- Air-box with upper and lower fuel injectors
- Total volume capacity is 9L

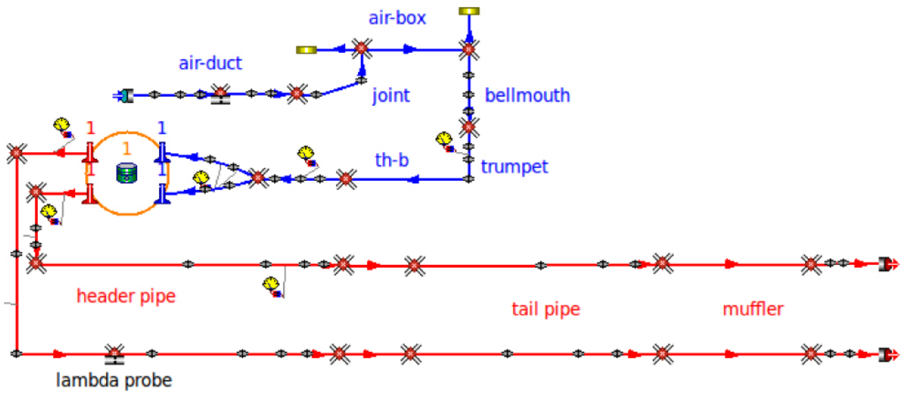
Starting point MY2017 (baseline)

State of the art of motorbike (championship 2017)

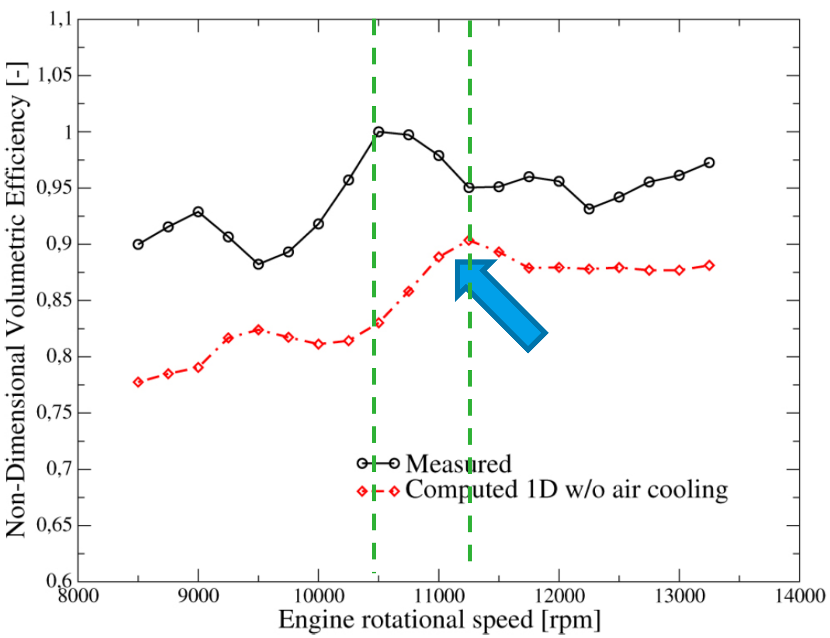


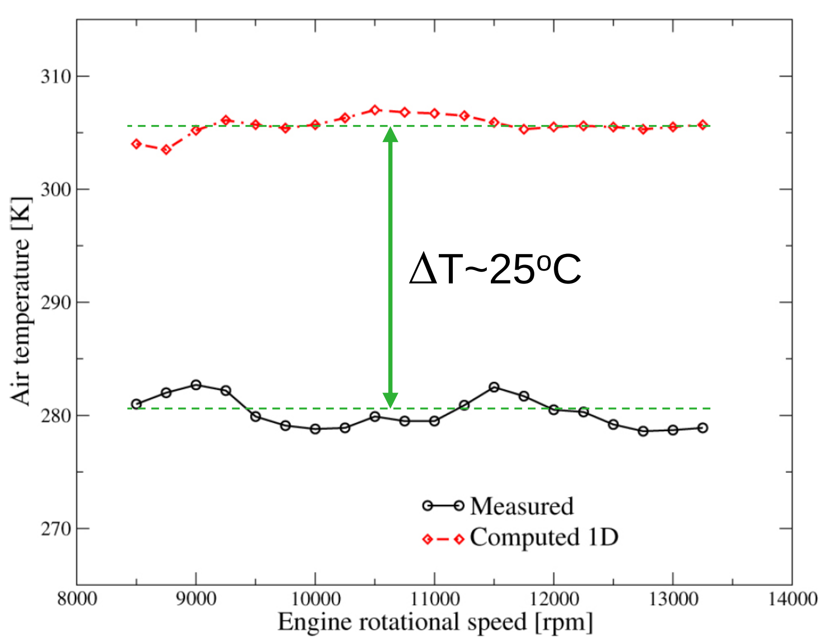
- Decrease of the overall air-box volume (7L from the original 9L)

Baseline 1D model: calibration



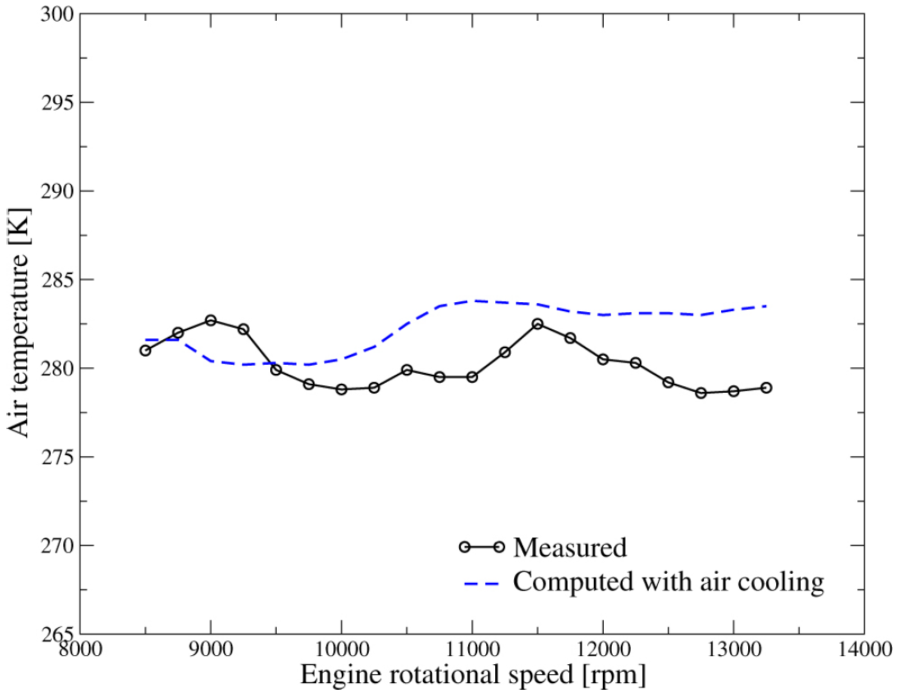
- Air temperature in the intake runner close to the ambient air
- Resonance frequency shifted towards higher engine speeds
- Fuel evaporation is the main cause of the shift

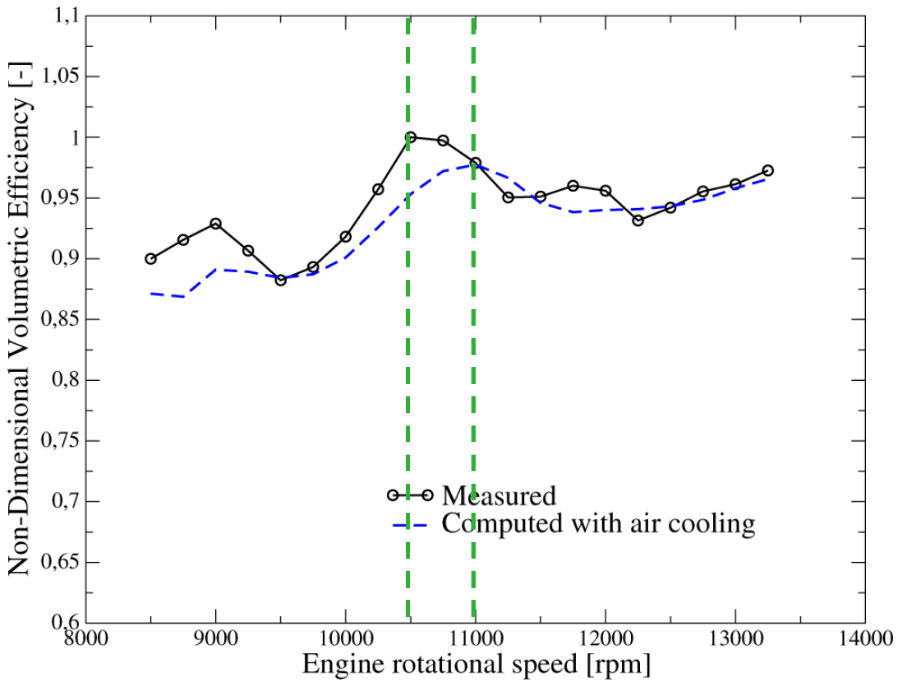




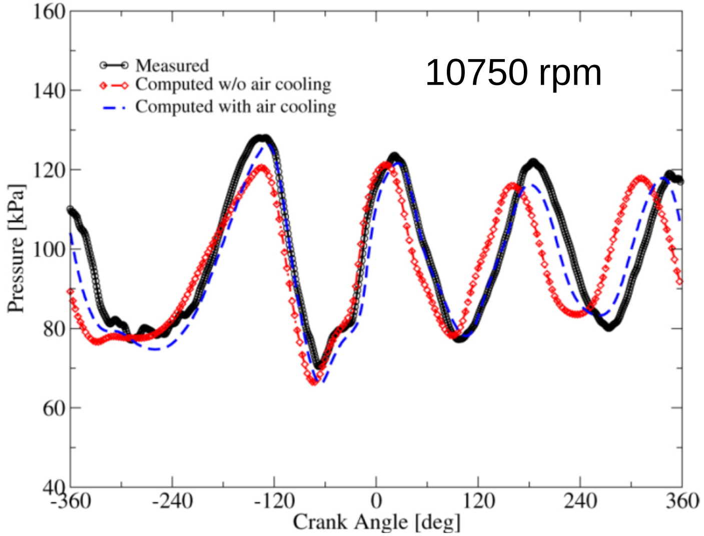
Model calibration: external heat source

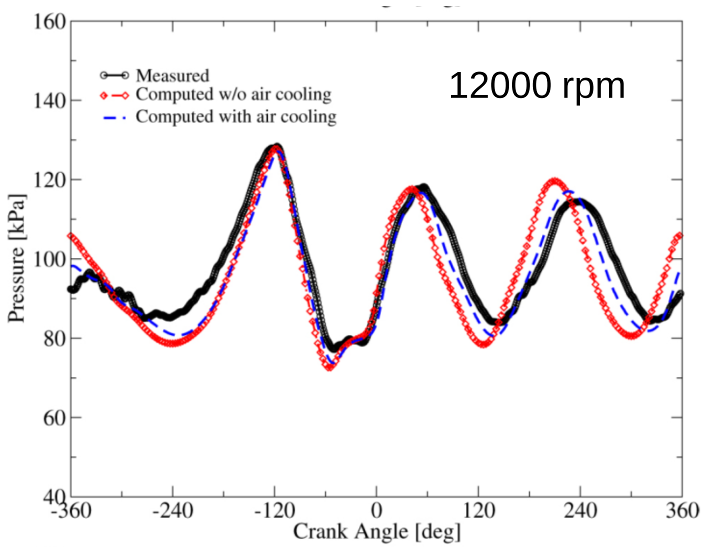
- Air is cooled down by playing with gas-wall heat transfer to mimic the cooling effect caused by the fuel evaporation.
- Low heat wall and multiplication factor for the convective heat transfer coefficient
- Careful tuning in order not to exceed with the cooling

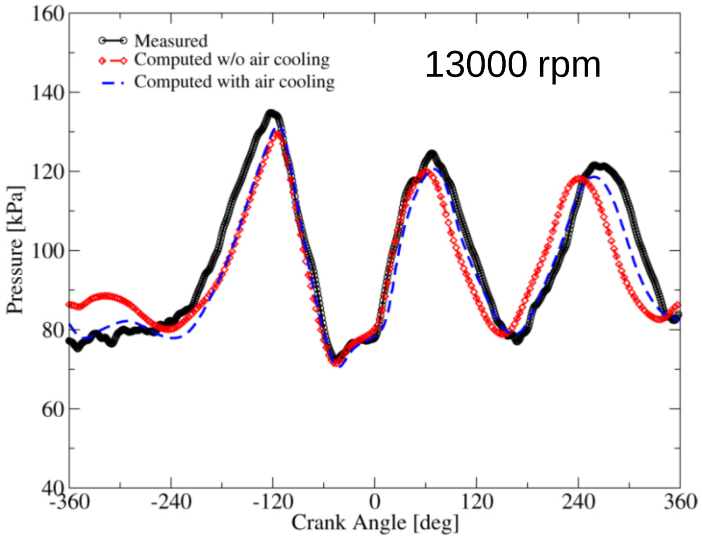




Comparison with experimental data: w and w/o cooling

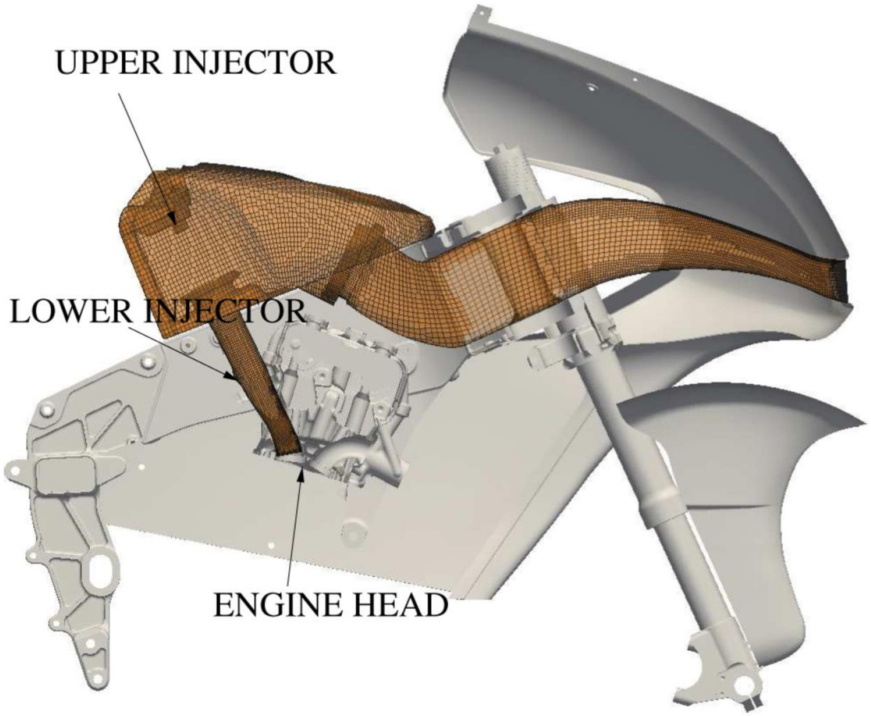


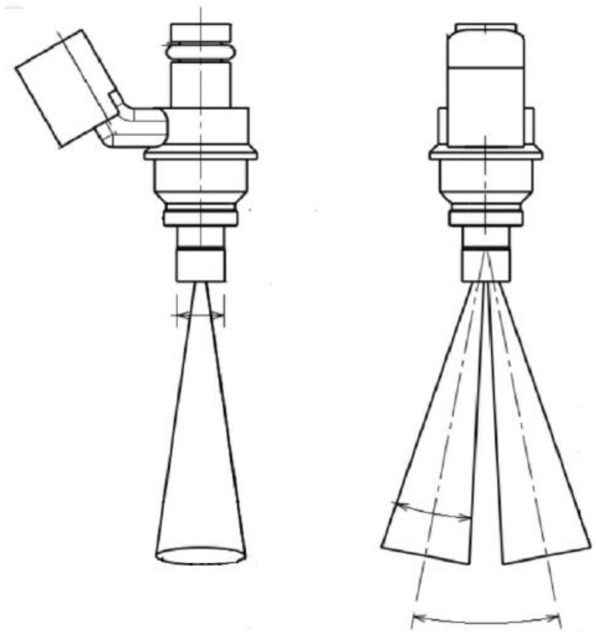




- Correct phasing of the closed valve resonance when cooling is introduced
- During valve opening the correction may overestimate supercharging effect

1D-3D coupling strategy





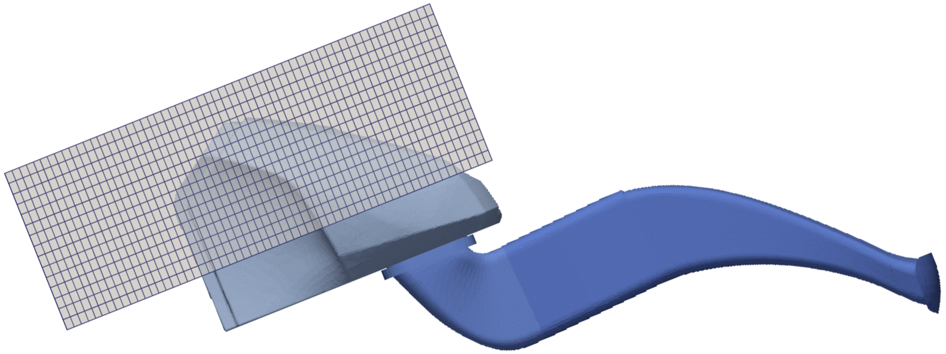
- The engine is equipped with two injectors: lower and upper
- Same SOI but different duration
- Coupling region close to engine valves

- Twelve holes injector
- Injection pressure 3.5 bar
- Pressure driven hollow cone injector, with an inner and outer angle

Meshing strategy

Automatic mesh generation

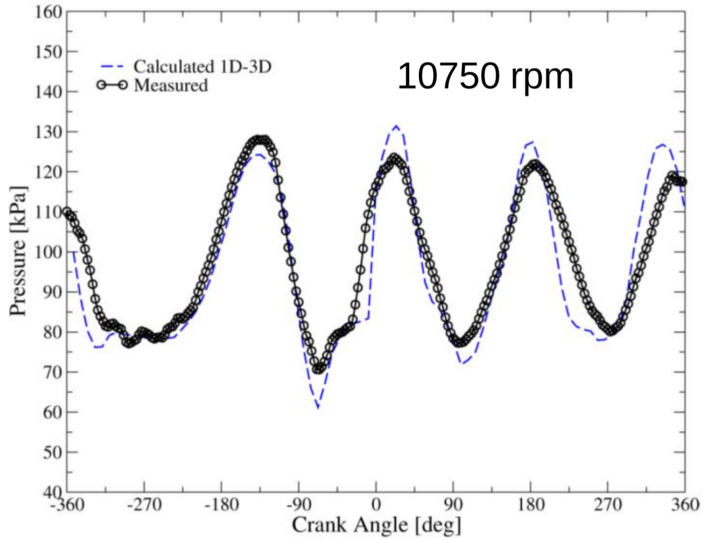
- Automatic mesh generation
- Hex dominated and composed by around 130000 cells with an average size of 3.5 mm.
- Low skewness, low non-orthogonality have been tailored along with grid-flow alignment

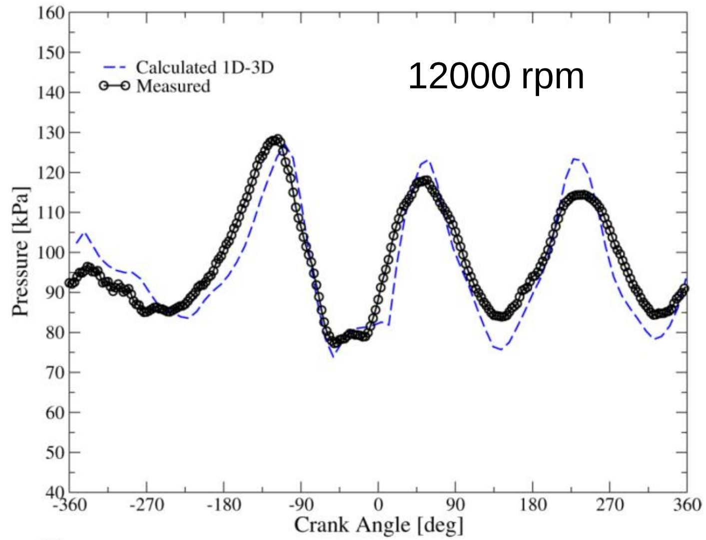


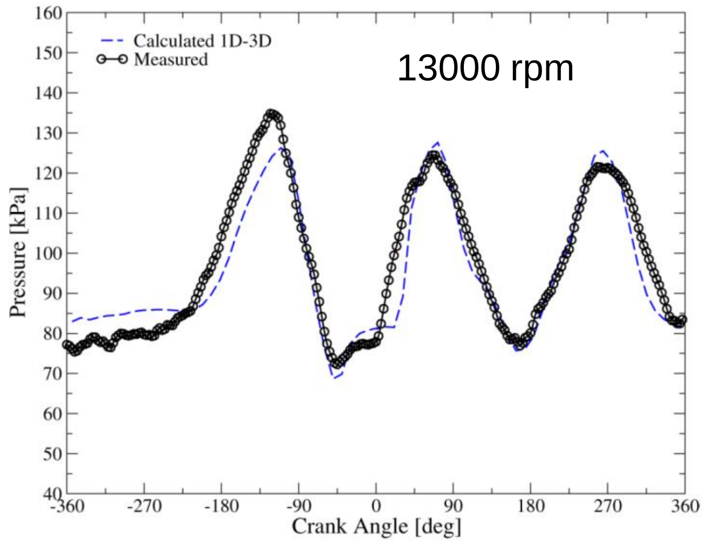
Remarks

- Block structured mesh
- Linear and curved extrusion of the base mesh to cover the whole geometry
- Castellated mesh stage followed by a snapping phase to accomodate points to the real shape

Comparison with experimental data: 1D-3D coupling

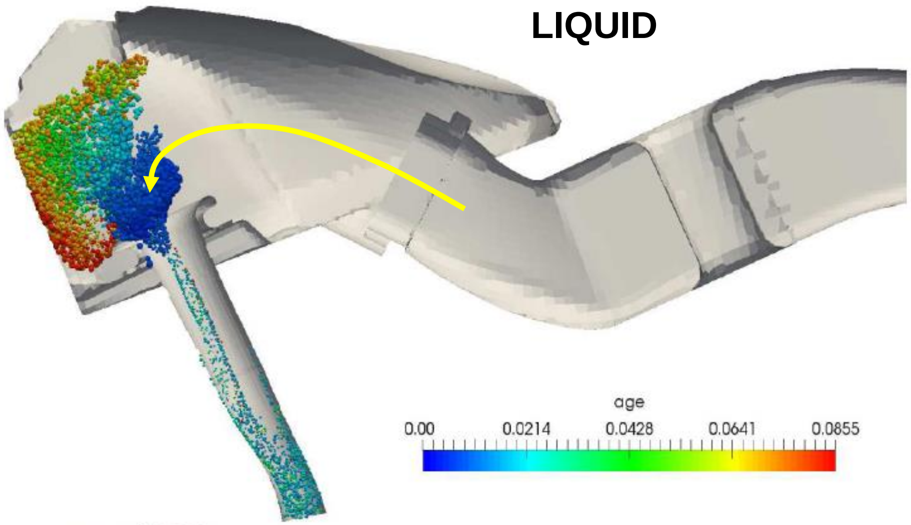


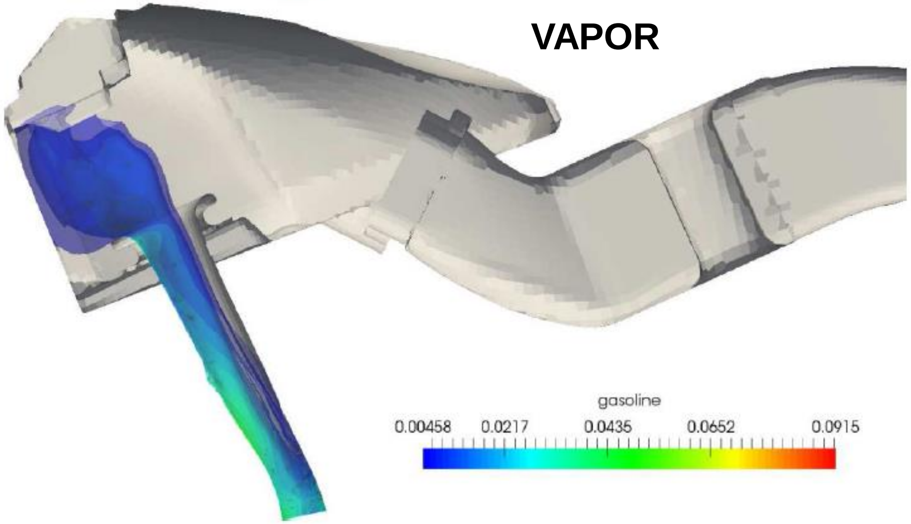




- Correct prediction of the gas temperature
- Phasing has improved due to the better modeling of the physics
- Less risk of overpredicting the air density increase

Fuel distribution





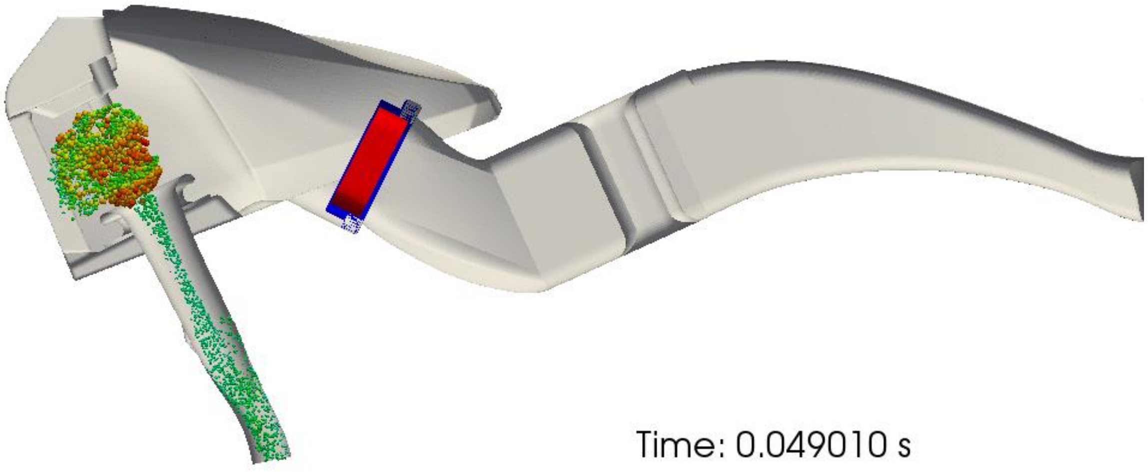
Considerations

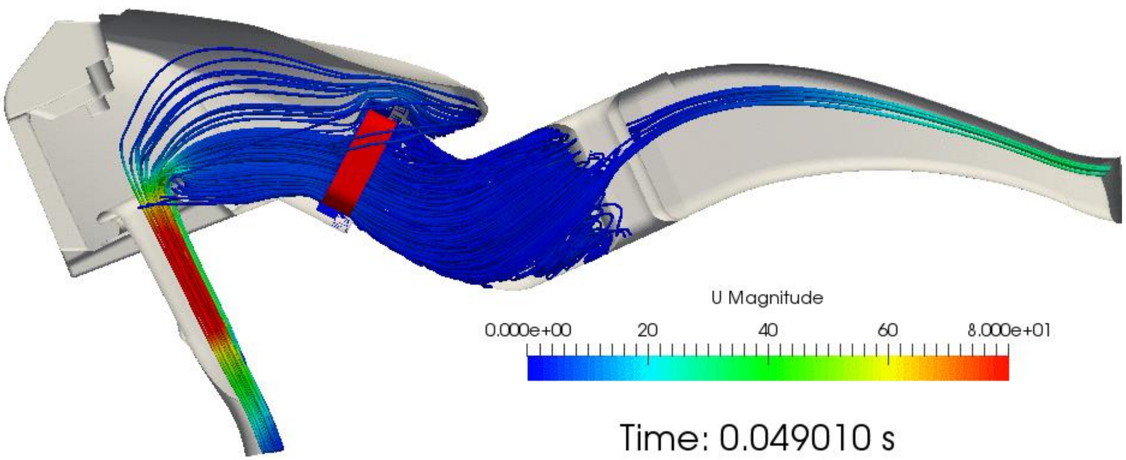
- Interaction between spray and flow field
- Flow field with high inertia
- Accumulation of fuel vapor in the rear part of the air-box

Cons:

- Slow response during transients
- Difficult control with auto lambda strategy

Optimization of the injection strategy: old SOI

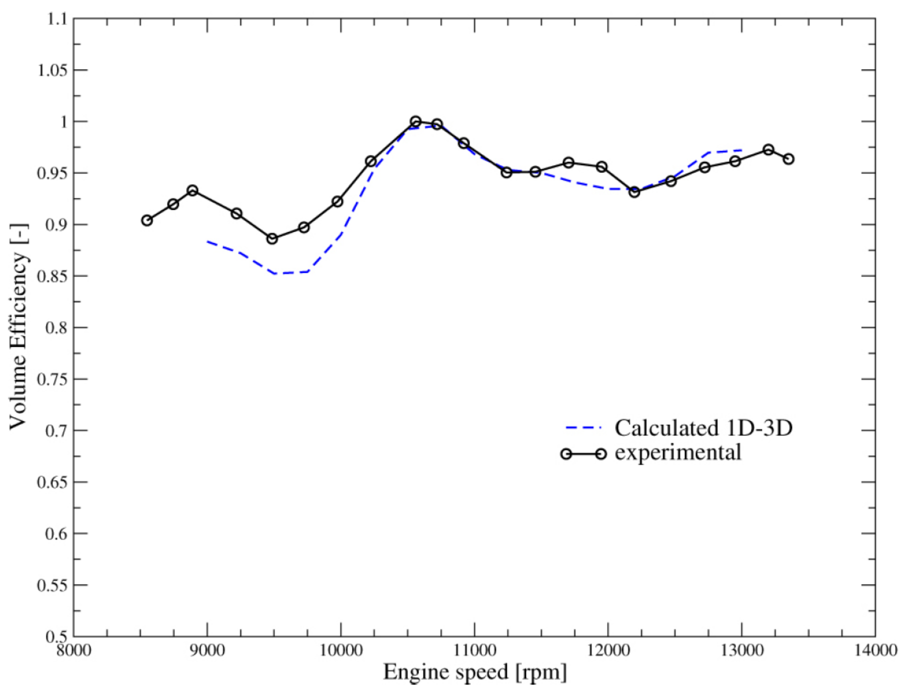


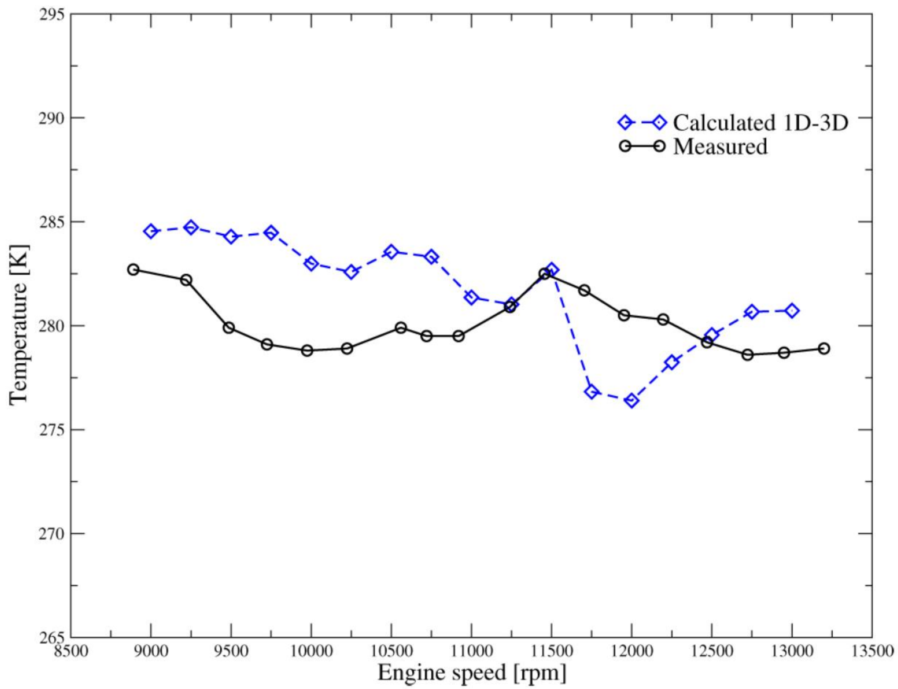


Considerations

- Drag action of the flow on low inertia particles
- Latest part of the injection occurs with a badly phased timing

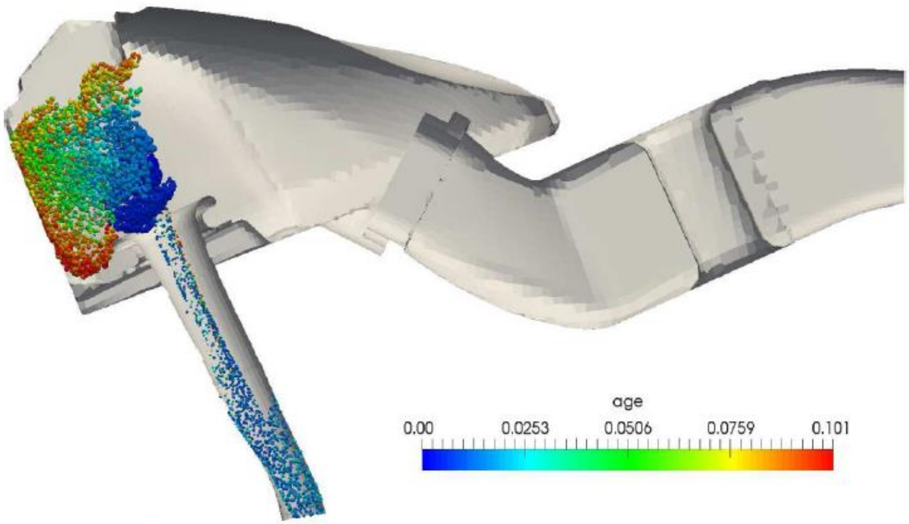
Comparison with measured results

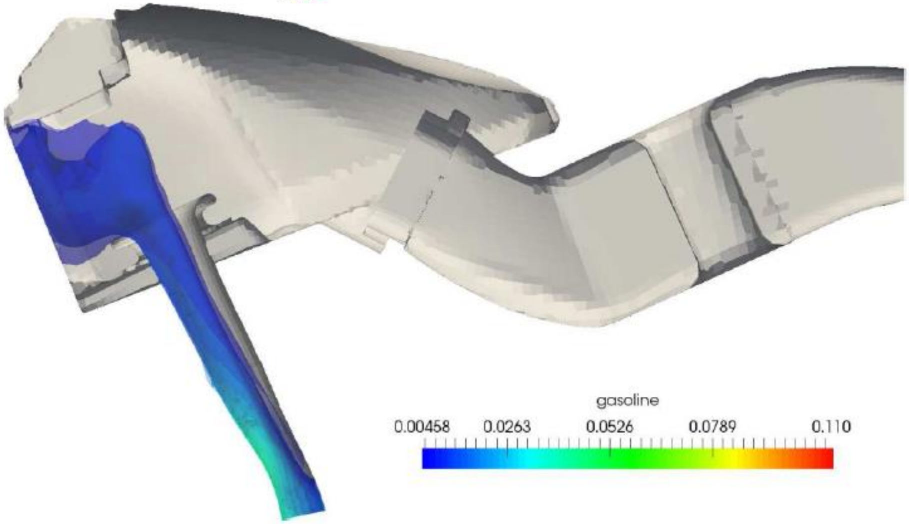




- Better prediction of the gas temperature, hence of the volumetric efficiency
- Trend with the engine speed is captured
- Discrepancies: fuel properties, wetting of the probes…

Some preliminary conclusions





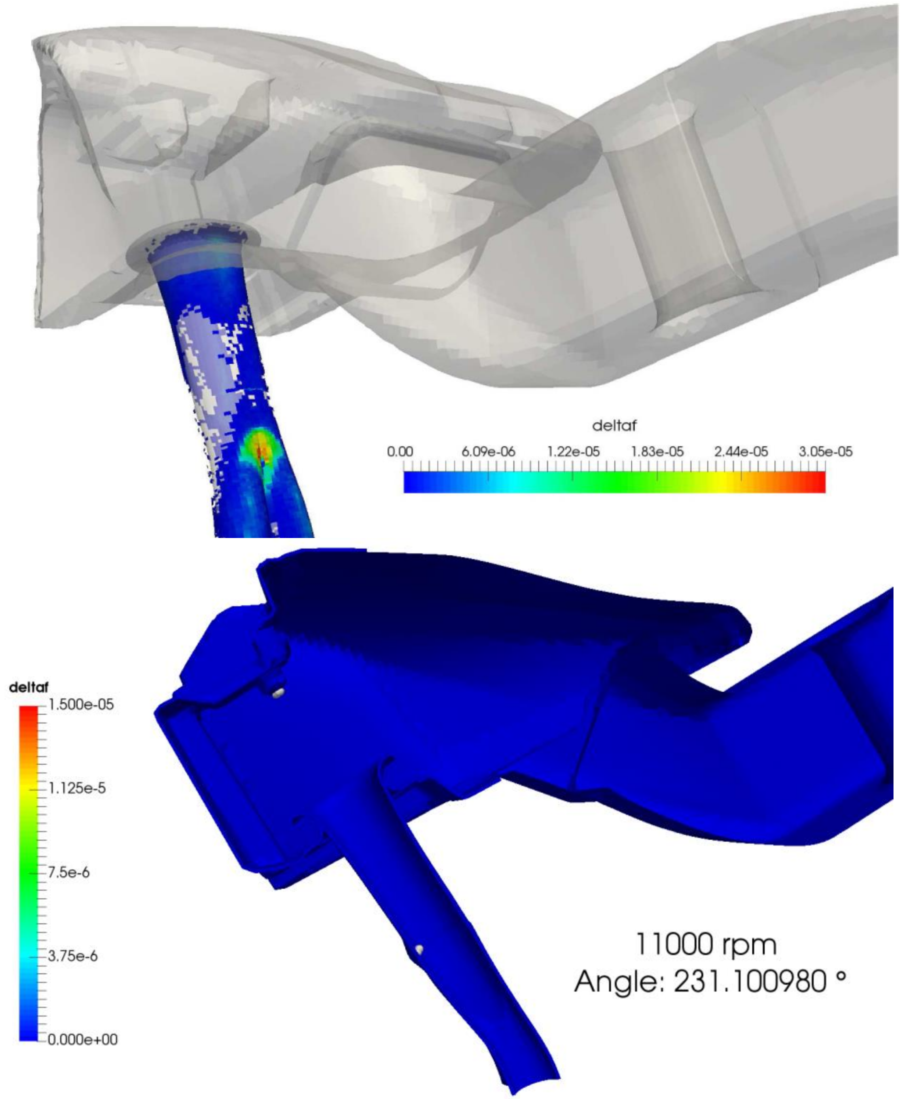
Considerations

- The oldest parcels belong to 4 injections ahead
- Only parcels with low inertia (small diameter) are dragged away from the target

Actions:

- Decouple the spray from the gas flow:
  - Baffles
  - Injector position
  - Injection timing

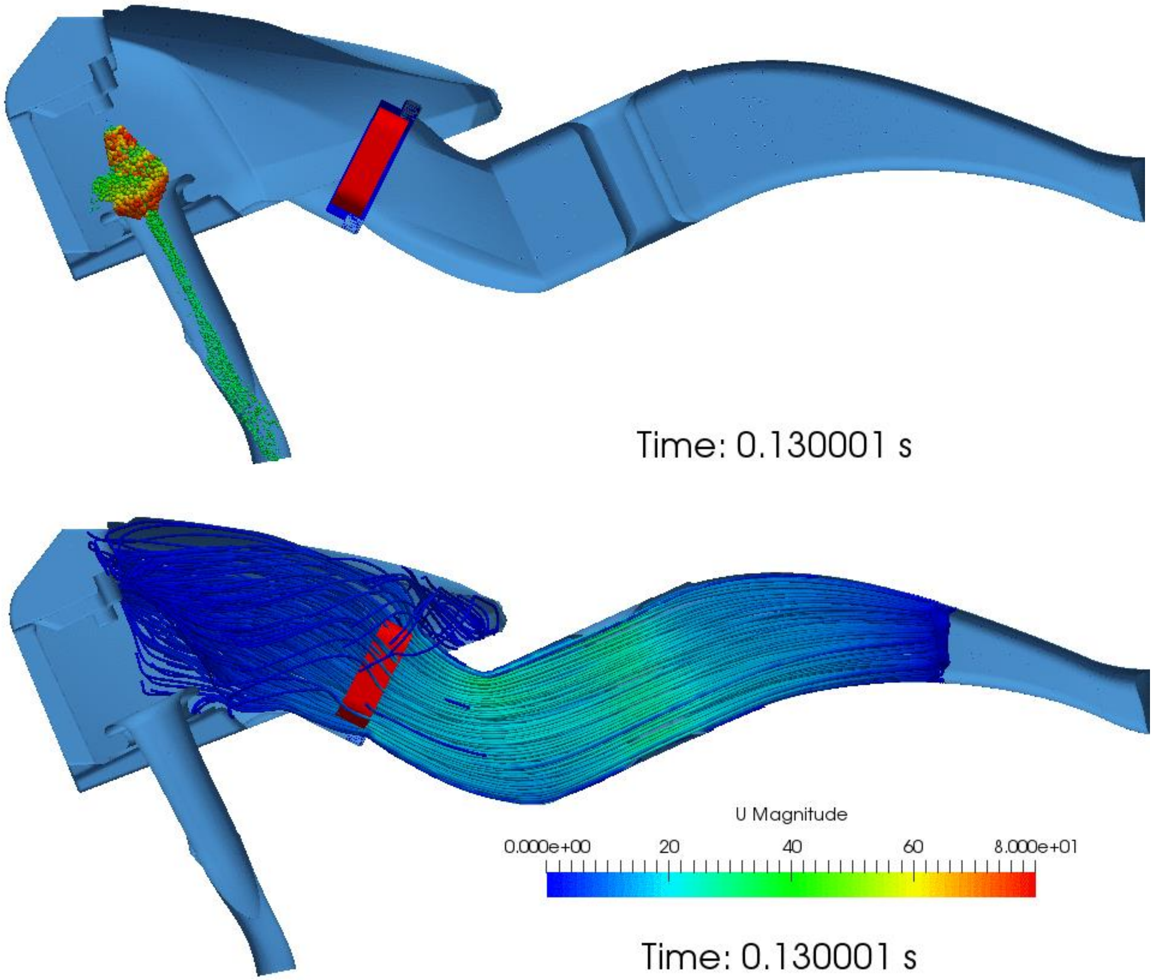
Liquid wall interaction



Outcomes

- Spray impacts with the wall mostly in the intake runner
- Considerable wetting for the lower injector
- No significant impact on the volumetric efficiency
- Wall temperature is imposed and kept fixed

Optimization of the injection strategy: new SOI



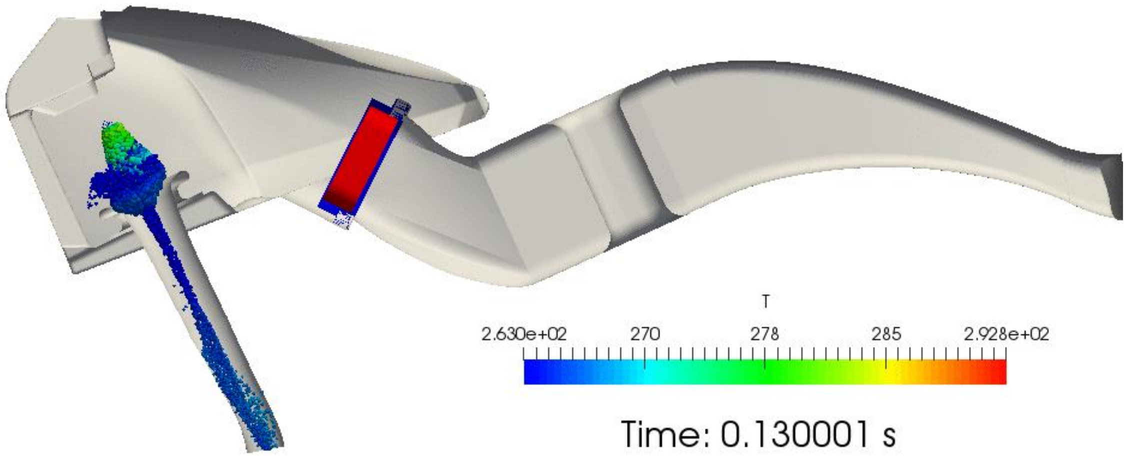
Inputs

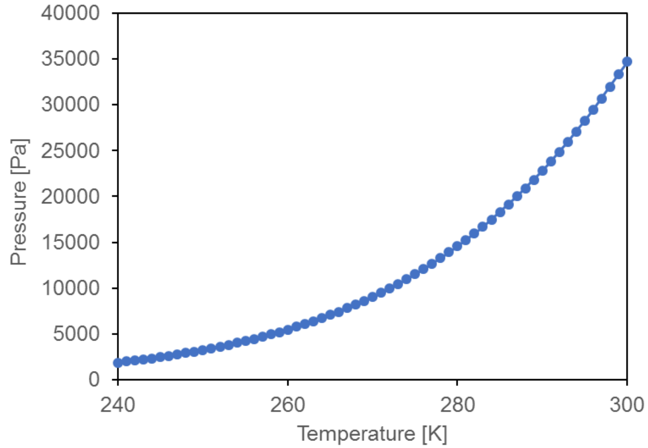
- SOI shifted in advance (50-100 c.a.d.)

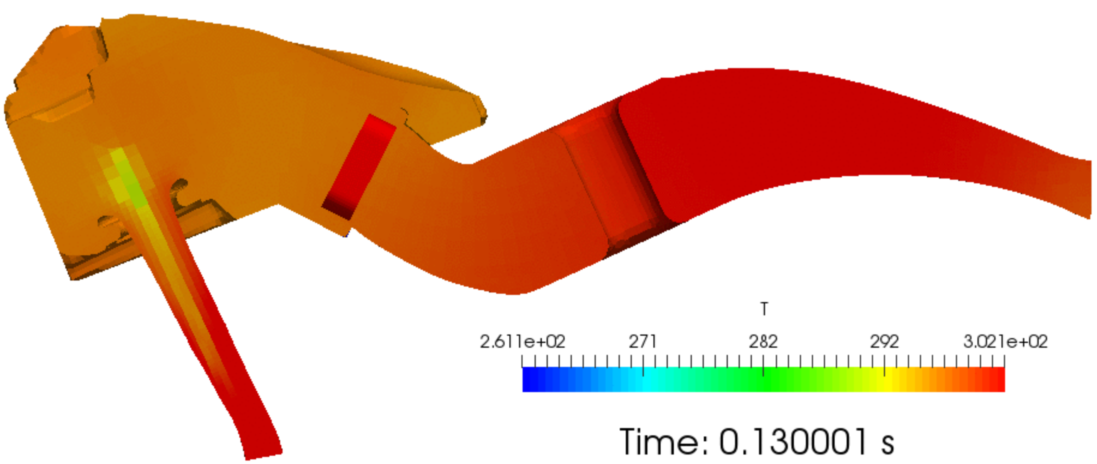
Considerations

- Reduction of the droplet dispersion during the injection
- Better behavior during transient operating condition
- Reduced interaction with the gas flow

Let’s draw some preliminary conclusion

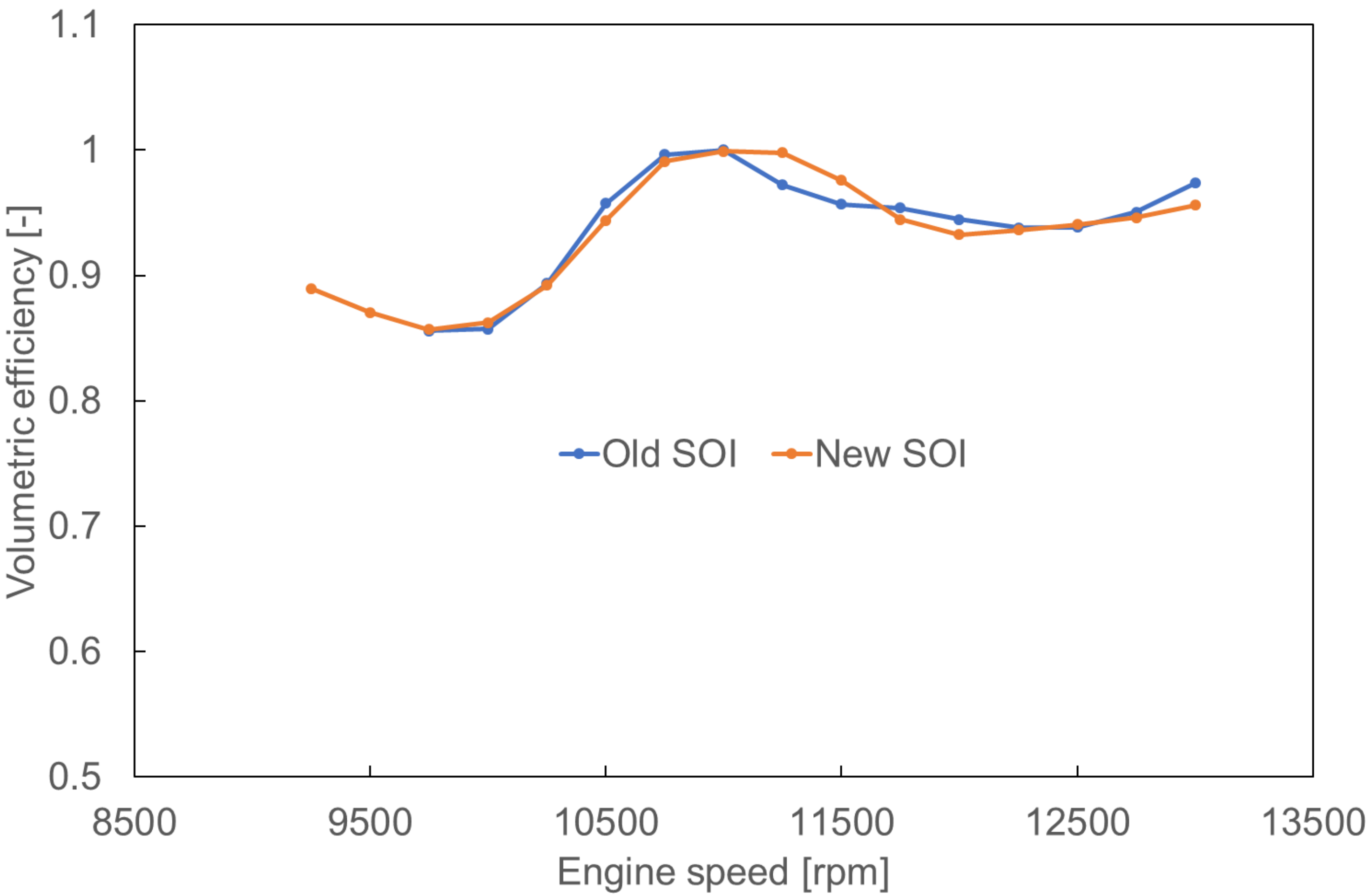




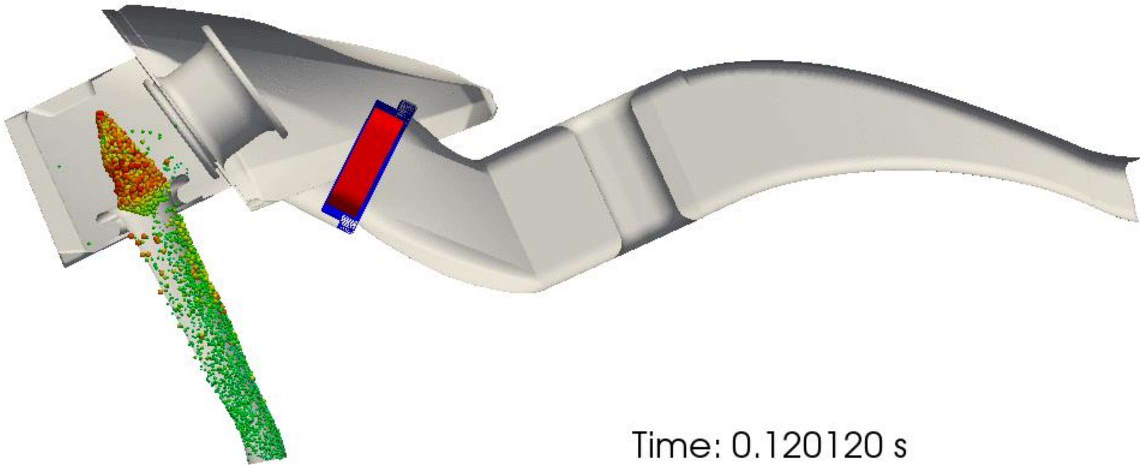


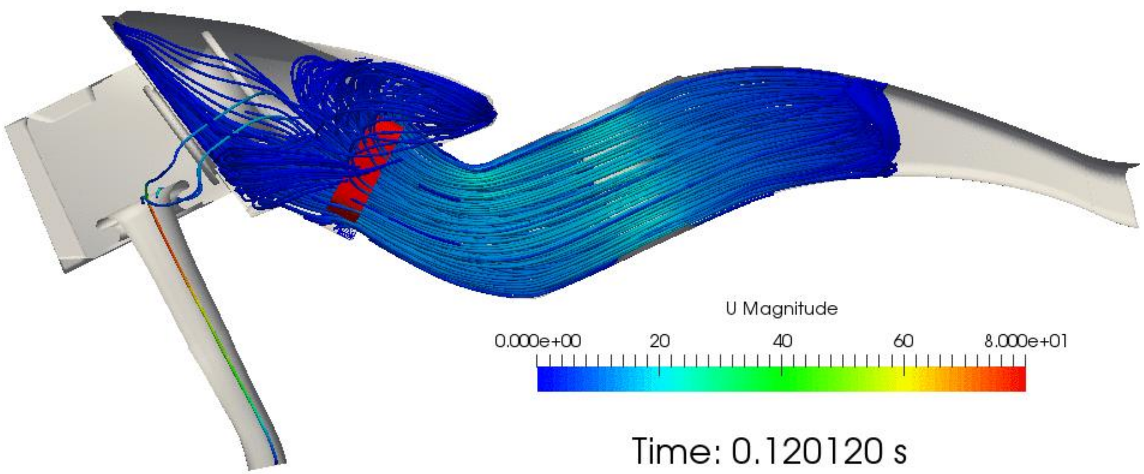
- Evaporation caused by cross flow injection (relative velocity between gas and droplets)
- Reduction of the pressure (0.7 bar) during closed valve period

Impact on volumetric efficiency



Optimized geometry: baffle





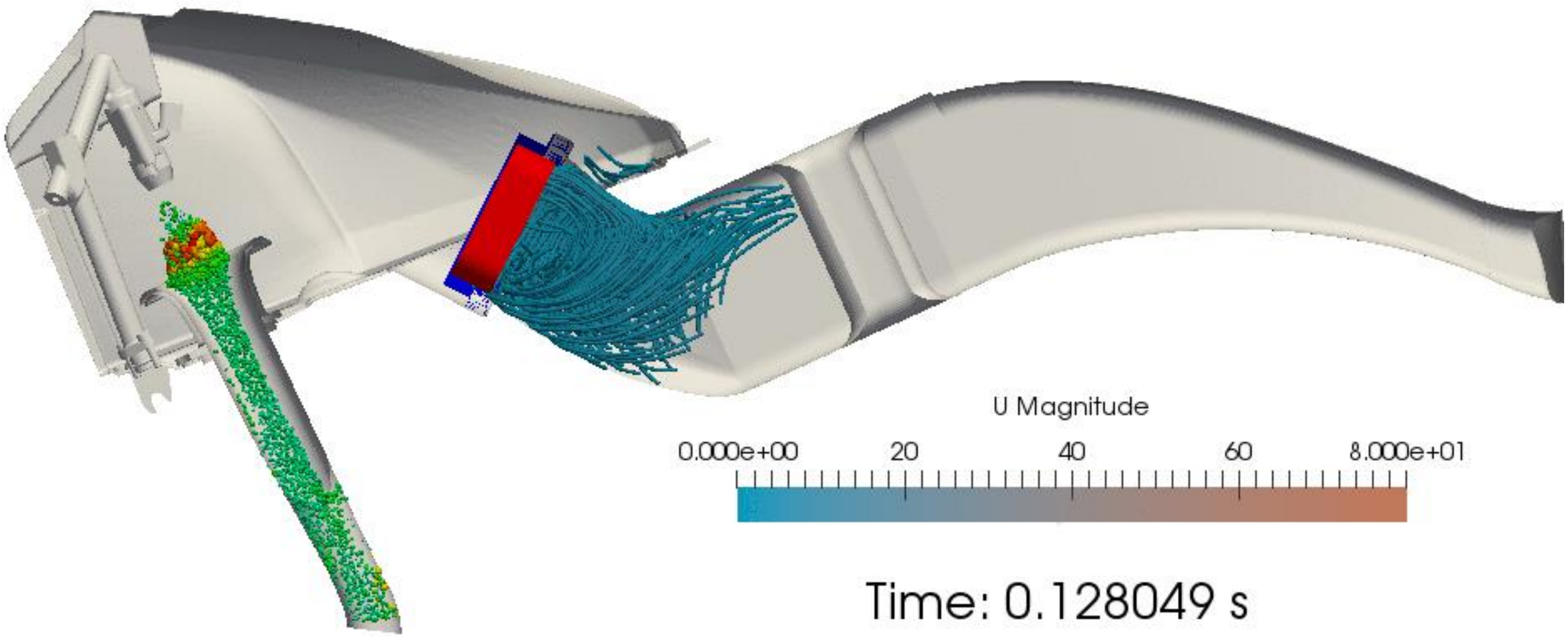
Input

- Including a baffle to create a "shield" effect

Considerations

- The baffle decouples the liquid droplets motion from the gas flow field
- Resonances to improve the volumetric efficiency
- Shape must be optimized to reduce pressure loss and flow detachments

Final configuration: timing and targeting optimized



- Advanced injection timing and lower position of the injector (closer to the intake runner open end)

CONCLUSIONS

- Analysis by means of coupled 1D-3D simulation, of the fuel spray propagation inside the air-box of a Moto3™ engine
- Investigate the influence of the fuel injection on the global engine performance as a function of the rotational speed, in order to understand specific phenomena that could be partially captured only by means of a fine calibration of a 1D model.
- The 3D simulation of the fuel injection has confirmed a local cooling effect due to the evaporation of the injected fuel during the intake valve closure period
- The value agrees with what is reported in the literature
- Better prediction of the volumetric efficiency: better capturing of the fresh charge density and better prediction of the closed valve wave action
- For a racing (and single cylinder) engine spray timing and targeting is a non-negligible parameter to be taken into account

THANK YOU