Third Two-Day Meeting on Internal Combustion Engine Simulations Using the OpenFOAM technology, Milan 22nd-23rd February 2018.

Gas exchange and fuel-air mixing simulations in a turbocharged gasoline engine with high compression ratio and VVA system

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Acknowledgements

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Topics

SI engines modeling using the OpenFOAM® technology

- Lib-ICE coupled with OpenFOAM
- SI engines simulation workflow
- Mesh generation and management
- Gas exchange and cold-flow
- Spray modeling and air-fuel mixture
- Gaseous fuel direct injection
- Next steps and conclusions

Lib-ICE and OpenFOAM

Internal combustion engine modeling using the OpenFOAM technology

OpenFOAM-x.x.x

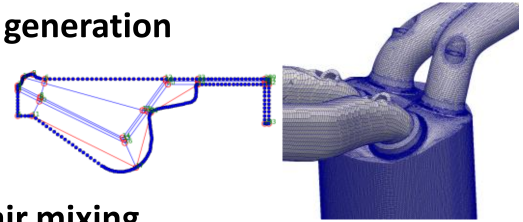
↓

Lib-ICE

- **Library**: physical models, mesh management
- **Applications**: solvers (cold flow, SI, Diesel, after-treatment), utilities

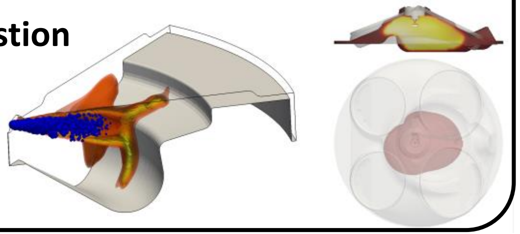
Engine simulation workflow

Mesh generation

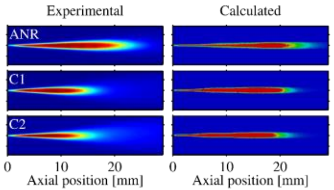


Fuel-air mixing

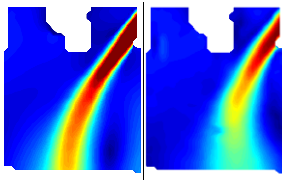
Combustion



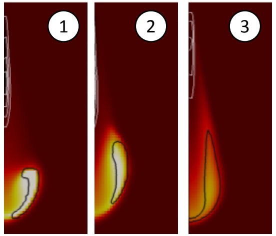
Development/validation



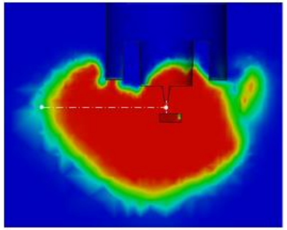
Spray modeling



Engine flows



Diesel combustion



SI combustion

SI engines: simulation workflow

Global overview

SI engines

Mesh management
- Automatic mesh generation
- Mesh motion
- Topological changes

Cold flow
- Discretization
- Turbulence models
- Mesh quality

Fuel-air mixing
- Lagrangian spray
- Sub-models
- Nozzle flow

Combustion
- Simplified or detailed kinetics
- Ignition
- Pollutants

SI engines: simulation workflow

Specific overview

SI engines

Mesh management

- Automatic mesh generation
- Mesh motion
- Topological changes

Cold flow

- Discretization
- Turbulence models
- Mesh quality

Fuel-air mixing

- Lagrangian spray
- Sub-models
- Natural gas

Mesh generation and management

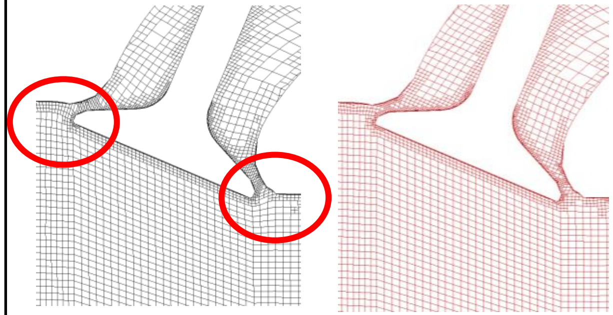
Global methodology

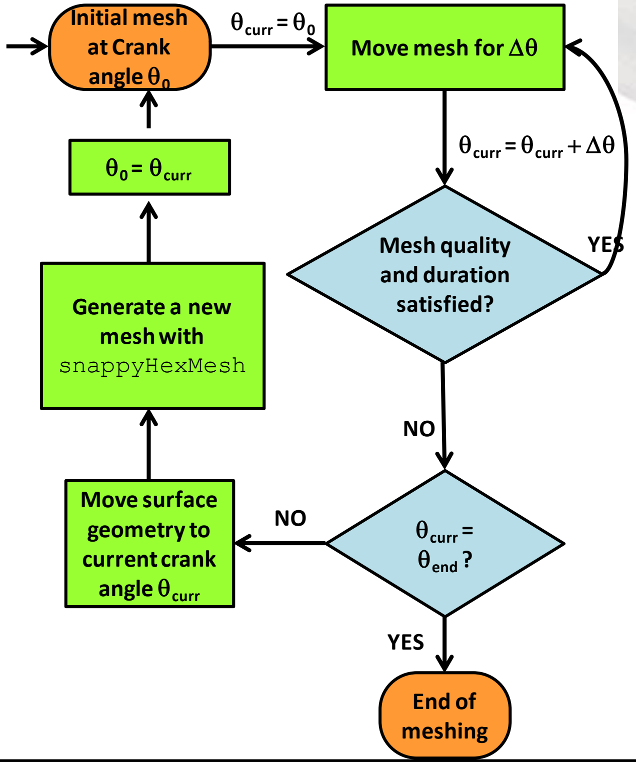
Full-cycle simulations:

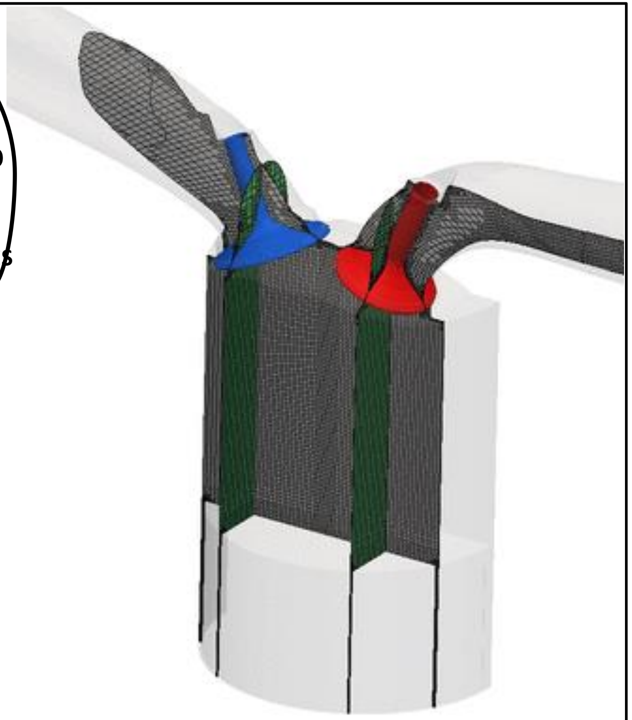
- Multiple meshes
- Mesh to mesh interpolation strategy.

Duration of each mesh:

- User defined + quality criteria



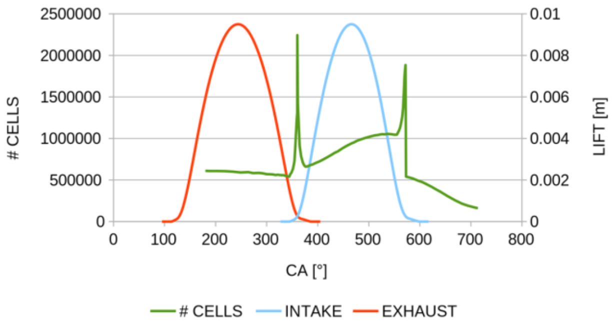




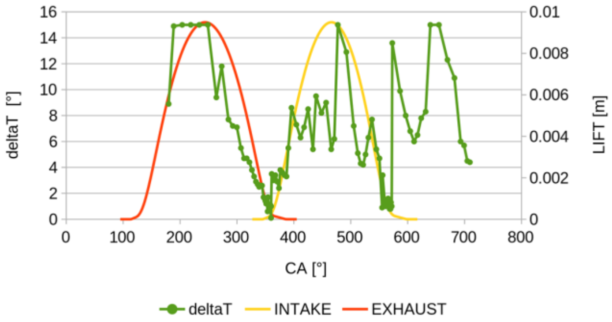
Mesh generation and management

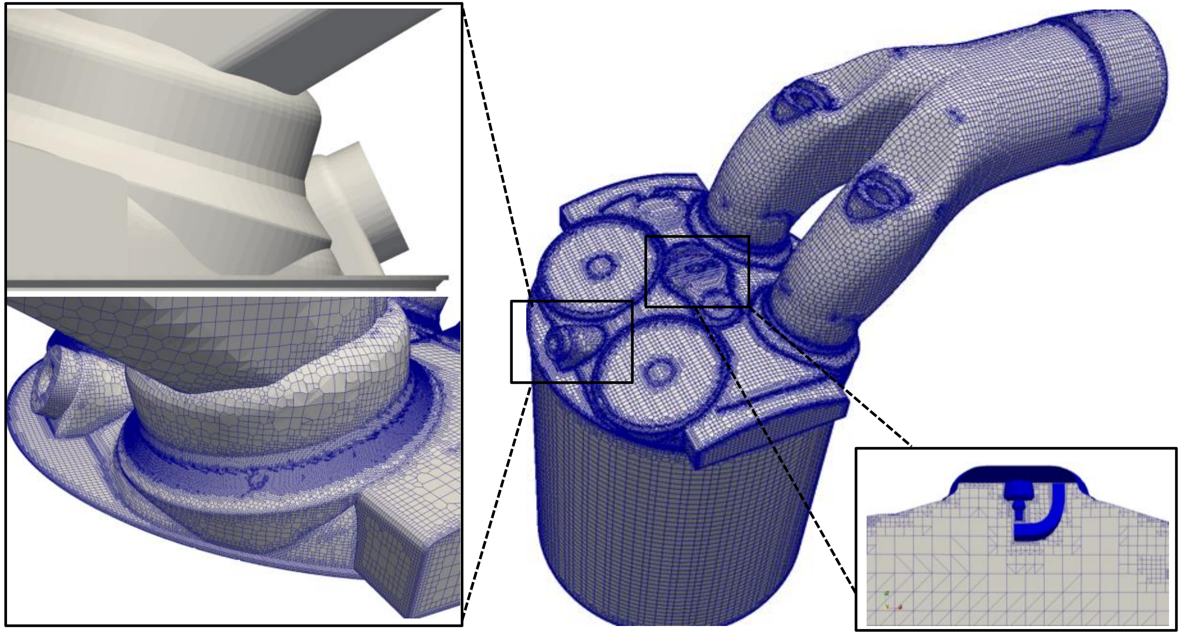
Mesh generation: IFP Energies nouvelles optical engine

Number of cells



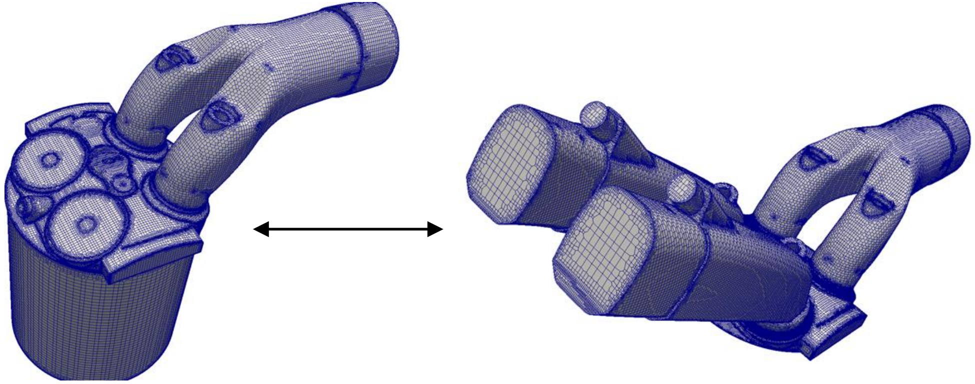
Mesh duration





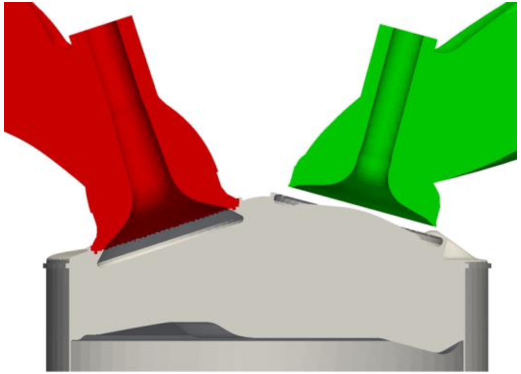
Mesh generation and management

Mesh manipulation: IFP Energies nouvelles optical engine and 1.0 liter, 3 cyl. VVA engine



IFP optical engine

- Multiple meshes
- Mesh to mesh interpolation strategy
- Ducts are removed when not used
- 1 mm internal cell size
- 0.5 mm internal cell size under the injector
- Local refinement down to 0.125 mm at the valves



1.0 liter, 3 cyl. VVA engine

- Unsteady flow in detached ducts is simulated along with the engine
- Pressure waves helping cylinder filling are taken into account
- Fuel backflow into the intake ducts is taken into account

SI Engines: cold flow

1.0 liter, 3 cyl. VVA engine: case set-up and validation

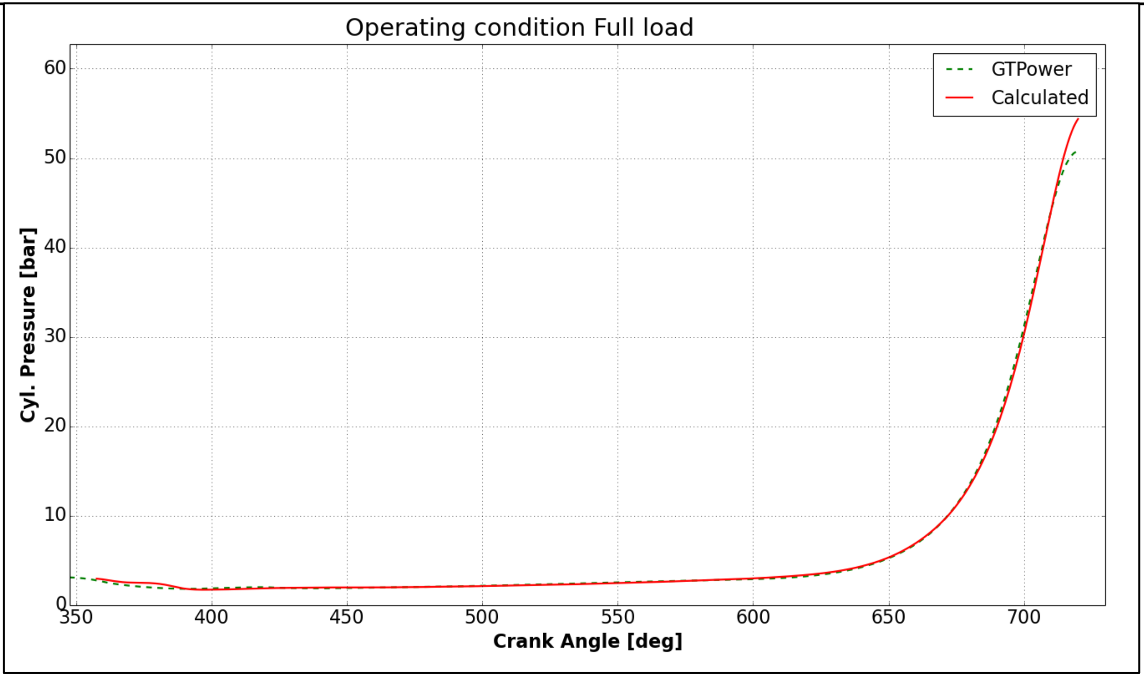
CFD setup

- **Second-order** numerical schemes
- Turbulence model: **standard k-ε**
- **Unsteady BC** imposed at inlet and outlet ports on the basis of data provided by **GT-POWER** simulations

Tested operating conditions

Partial load	2000 rpm
Full load	5500 rpm
Intermediate load	4000 rpm

Presented in this work



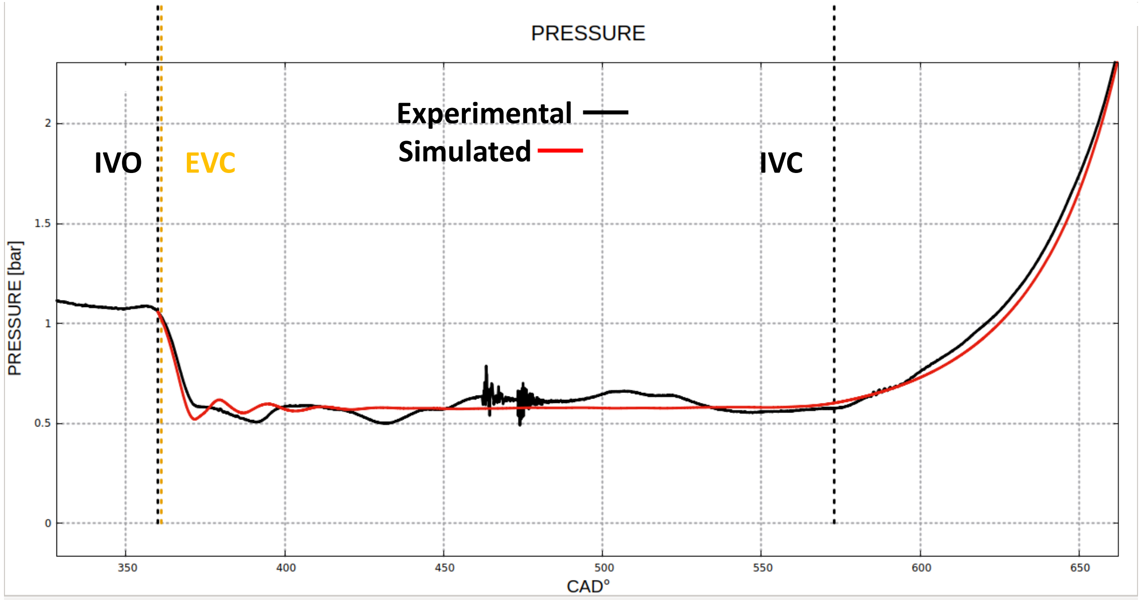
Validation by **comparing computed** and **experimental data** of in-cylinder pressure during gas exchange and compression processes

SI Engines: cold flow

IFP optical engine: geometry data, case set-up and validation

IMEP	4.7 bar
Intake pressure	0.58 bar
Exhaust pressure	1.03 bar
IVO	360 CA
IVC	573 CA
EVO	129 CA
EVC	361 CA
Engine speed	1200 rpm
Equivalence ratio	0.99

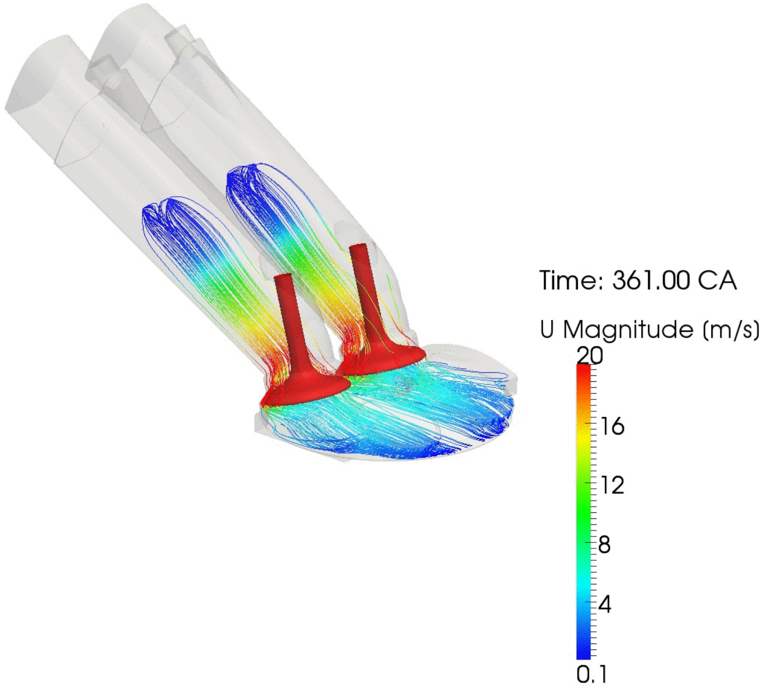
- **Second-order** numerical schemes
- Turbulence model: **standard k-ε**
- **Unsteady BC** (from experimental data) imposed at inlet and outlet ports



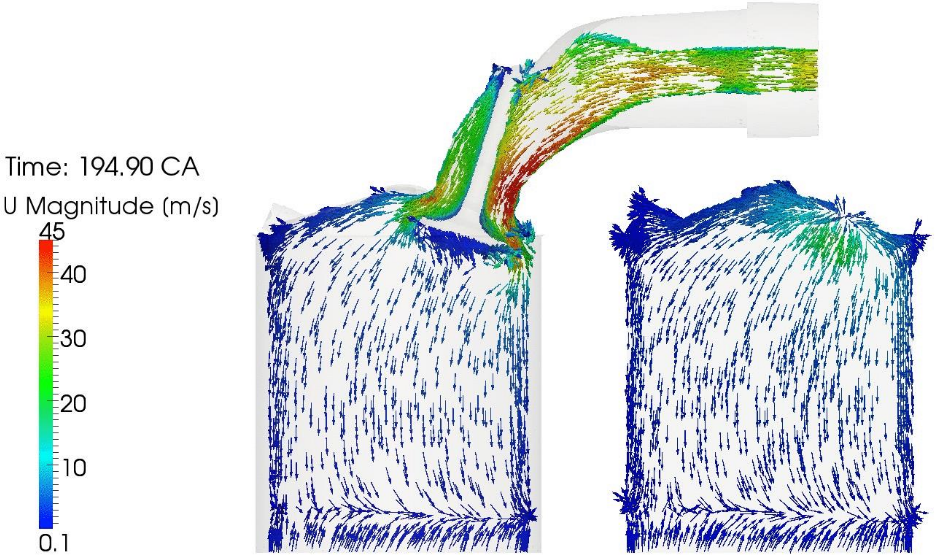
Validation by **comparing computed** and **experimental data** of in-cylinder pressure during gas exchange and compression processes

SI Engines: cold flow

IFP optical engine: flow field post processing



Intake flow streamlines and in-cylinder velocity vectors for a plane cutting through the valves stem



SI Engines: spray modeling

Spray targeting in vessel: ECN Spray G

- Modeling of ECN multi-hole GDI injector: it stands at the basis of GDI engines spray calibration activities
- Baseline ECN Spray G condition
- Engine-like conditions (experimental data from Istituto Motori CNR)

Case	(p_{inj}) [bar]	(ρ_{amb}) $\left[\frac{kg}{m^3}\right]$	(T_{amb}) [K]
Case 1 (ECN)	200	3.5	573.15
Case 4	200	3.5	473.15
Case 5	200	3.5	473.15
Case 6	200	3.5	373.15
Case 7	200	3.5	333.15
Case 8	150	3.5	573.15
Case 9	150	3.5	333.15
Case 10	150	1.0	333.15
Case 11	100	1.0	333.15
Case 12	50	1.0	333.15

CFD setup

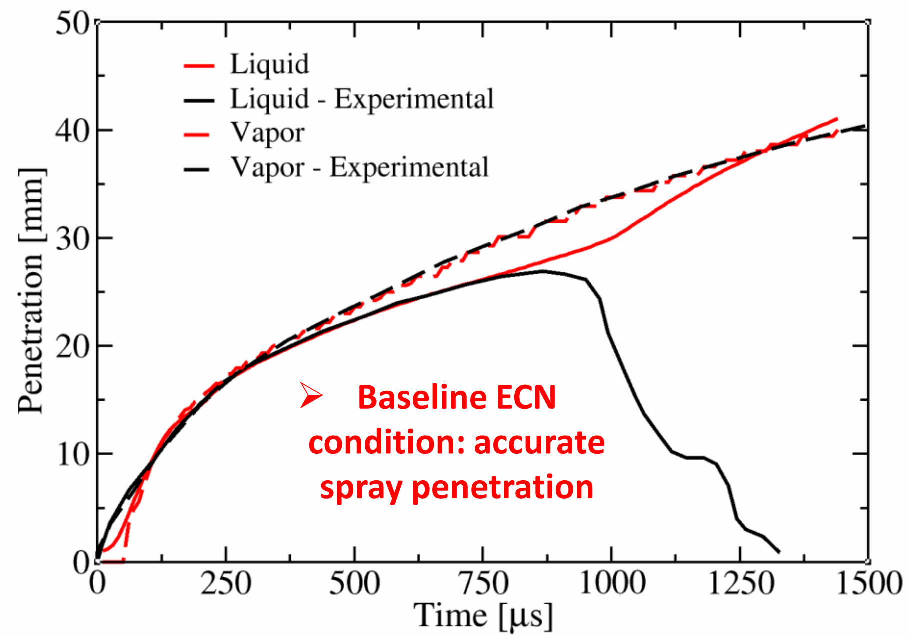
Injection model	Lagrangian Huh
Atomization model	Huh-Gosman
Secondary break-up	Reitz-KHRT or Reitz-Diwakar
Type of mesh refinement	Adaptive (AMR)
Base cell size	4 mm
Minimum cell size	1 mm or 0.5 mm

- Fuel: IC8H18
- Turbulence model: standard k-Ɛ
- C1 = 1.44
- 3D computational mesh

SI Engines: spray modeling

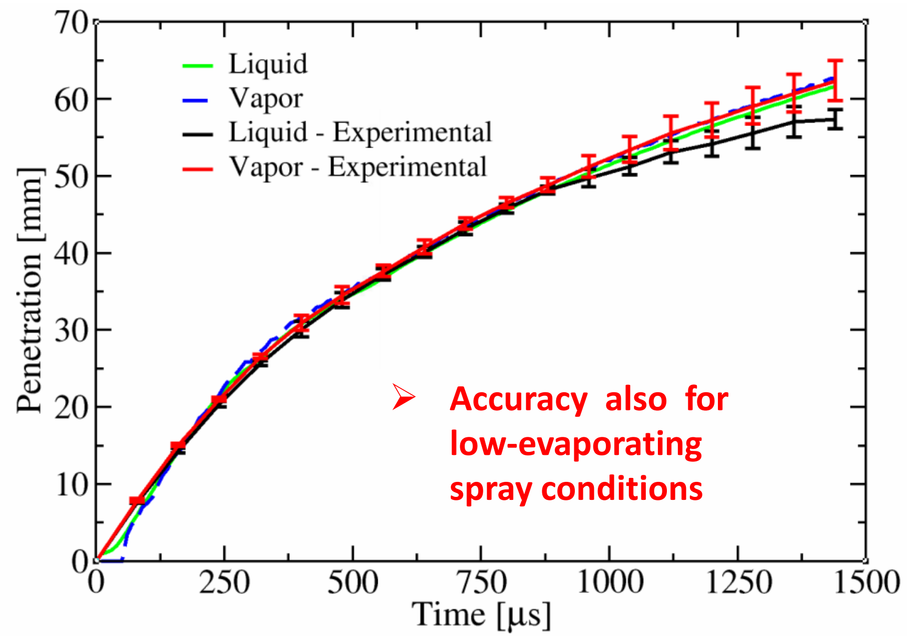
ECN Spray G: spray penetration for ECN baseline and low-evaporating cases

Case	(p_{inj}) [bar]	(ρ_{amb}) $\left[\frac{kg}{m^3}\right]$	(T_{amb}) [K]
Case 1 (ECN)	200	3.5	573.15



- Baseline ECN condition: accurate spray penetration

Case	(p_{inj}) [bar]	(ρ_{amb}) $\left[\frac{kg}{m^3}\right]$	(T_{amb}) [K]
Case 10	150	1.0	333.15

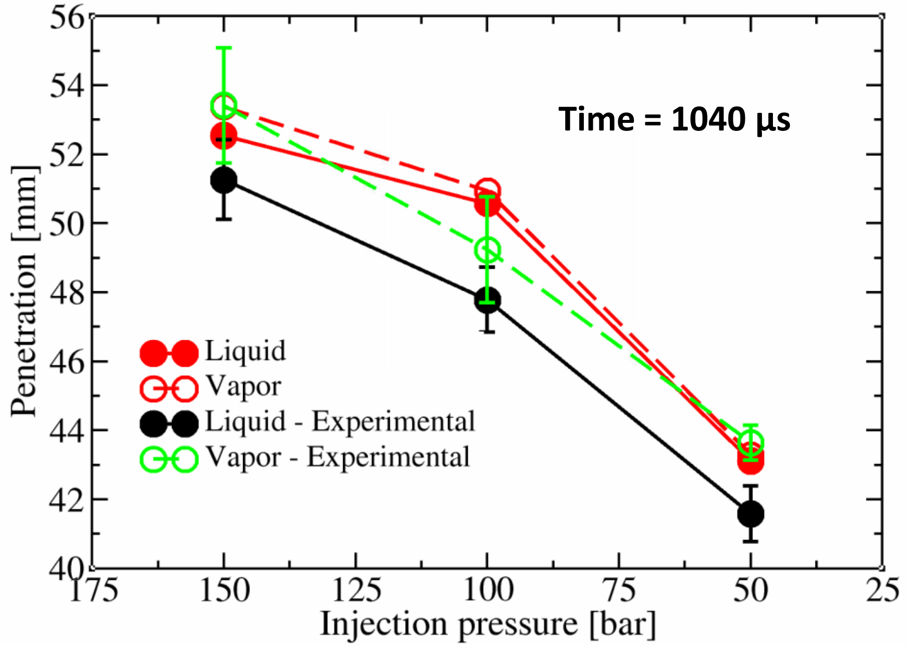


- Accuracy also for low-evaporating spray conditions

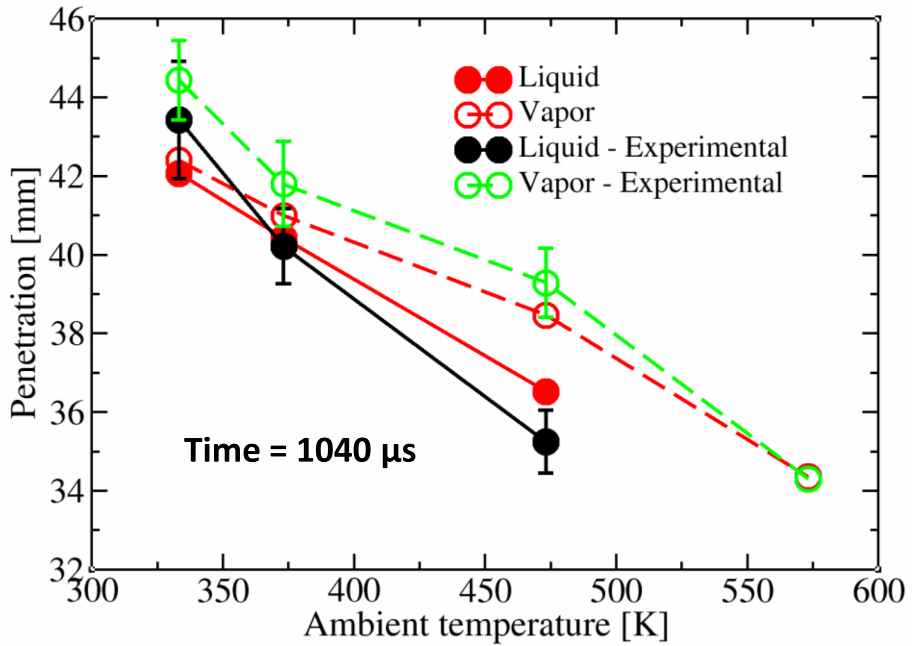
SI Engines: spray modeling

ECN Spray G: spray penetrations after EOI

Spray penetration after EOI (function of injection pressure)



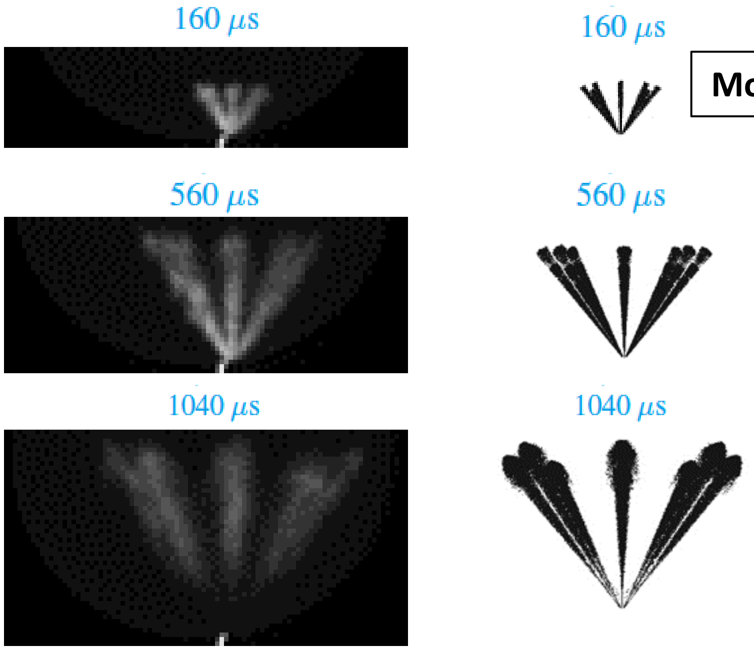
Spray penetration after EOI (function of ambient temperature)



SI Engines: spray modeling

ECN Spray G: morphology and SMD

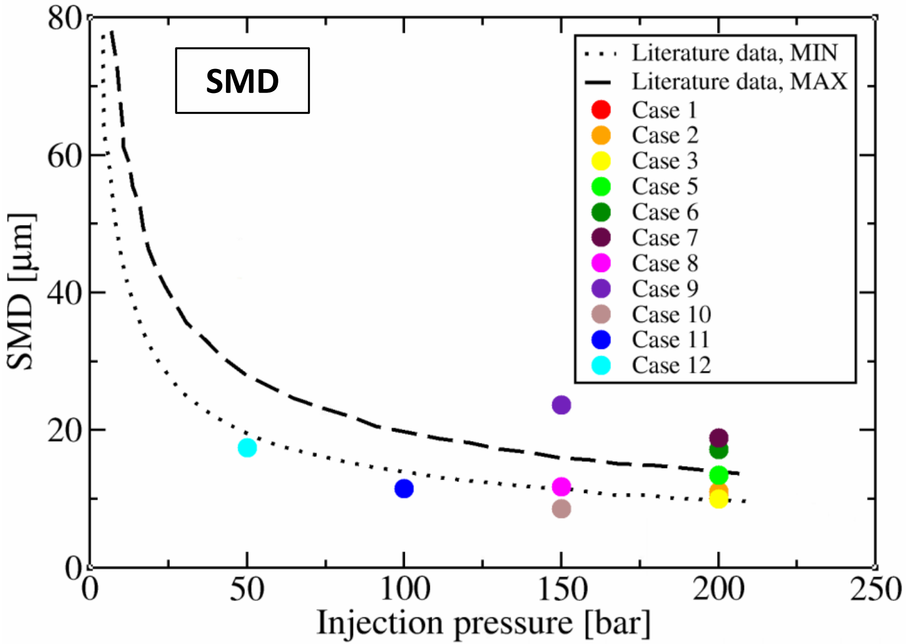
Case	(p_{inj}) [bar]	(ρ_{amb}) $[\frac{kg}{m^3}]$	(T_{amb}) [K]
Case 12	50	1.0	333.15



Morphology

- **Literature GDI injector experimental data [J. Hammer et al.]**

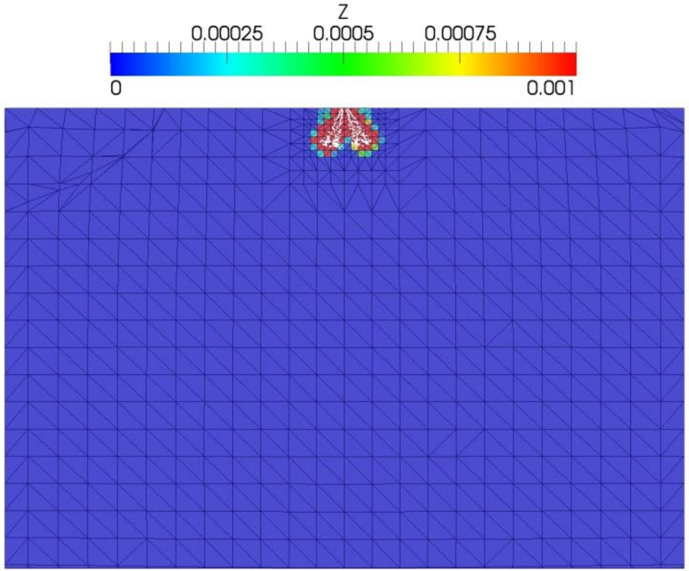
SMD

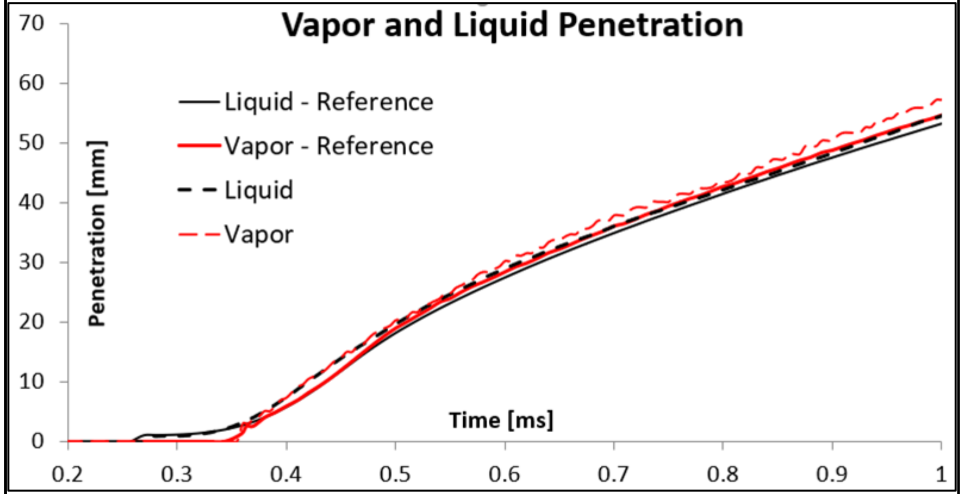


SI Engines: spray modeling

IFP optical engine: spray calibration

- **AMR** methodology
- **Liquid** penetration based on **mass**
- **Vapor** penetration based on **Z**



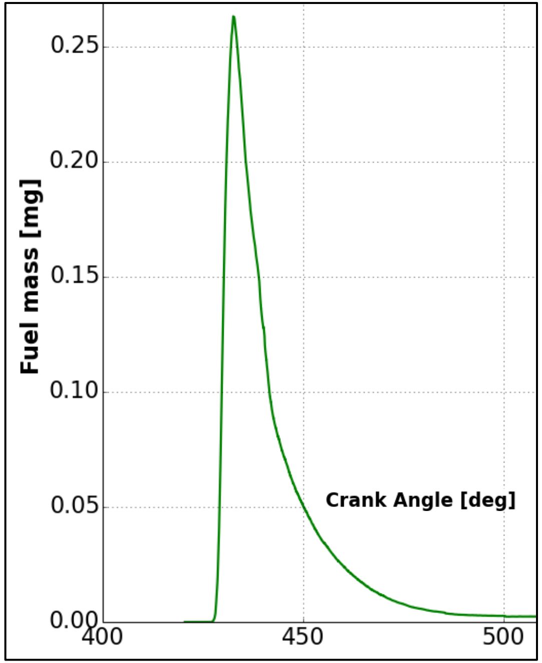


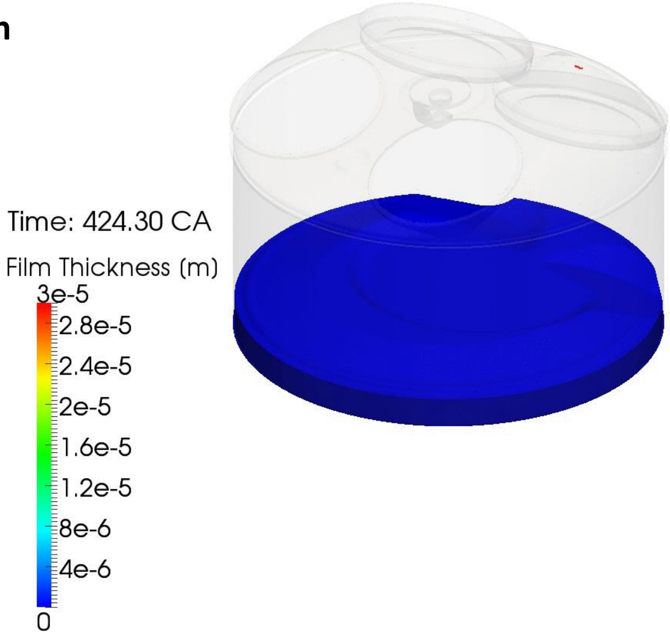
- Accurate prediction of **liquid and vapor penetration** values, matching the results of IFP reference commercial CFD code

SI Engines: GDI air-fuel mixing

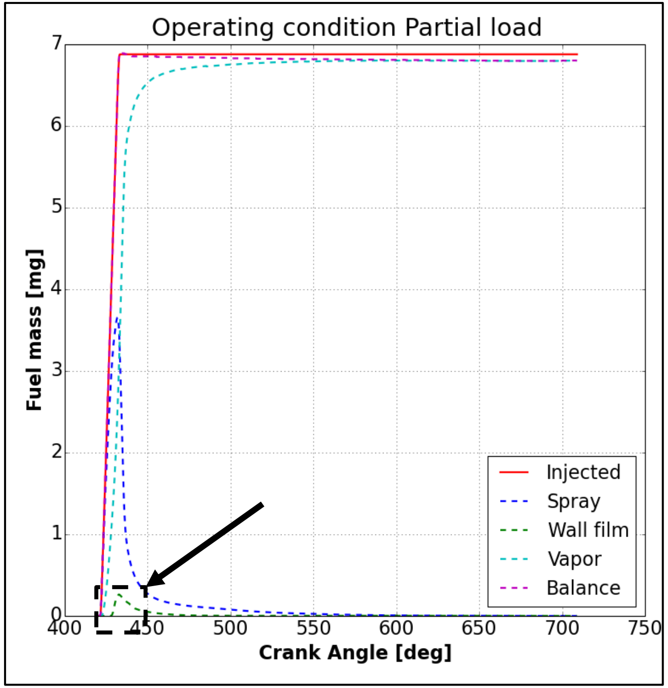
1.0 liter, 3 cyl. VVA engine – Partial load condition: fuel balance

- **Complete wall-film evaporation**



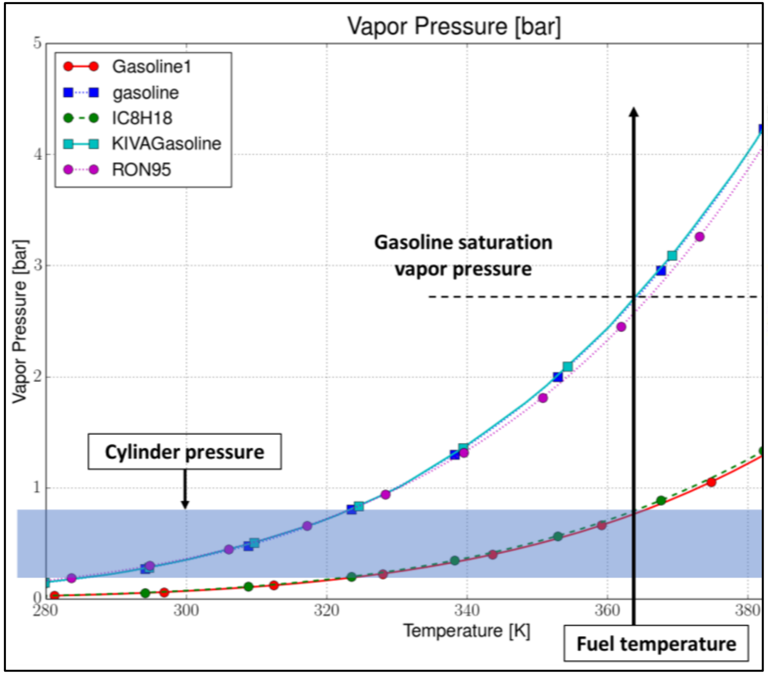


- **Accurate global fuel balance**

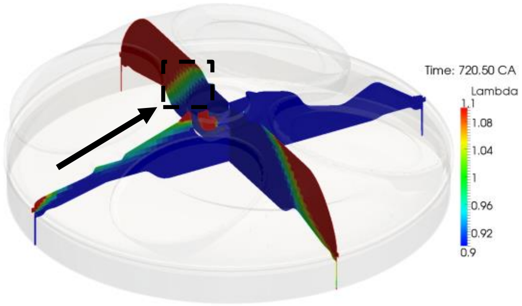


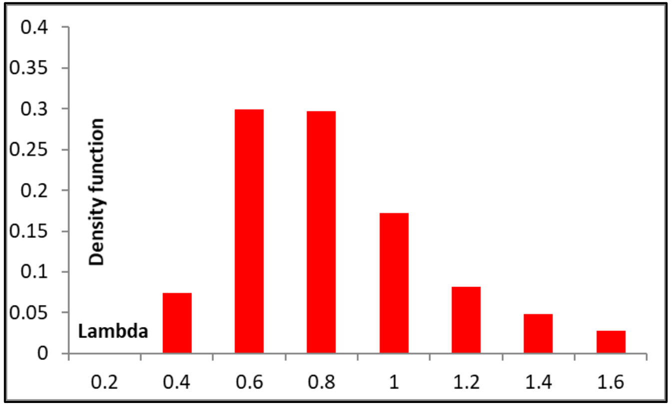
SI Engines: GDI air-fuel mixing

1.0 liter, 3 cyl. VVA engine – Partial load condition: mixture analysis



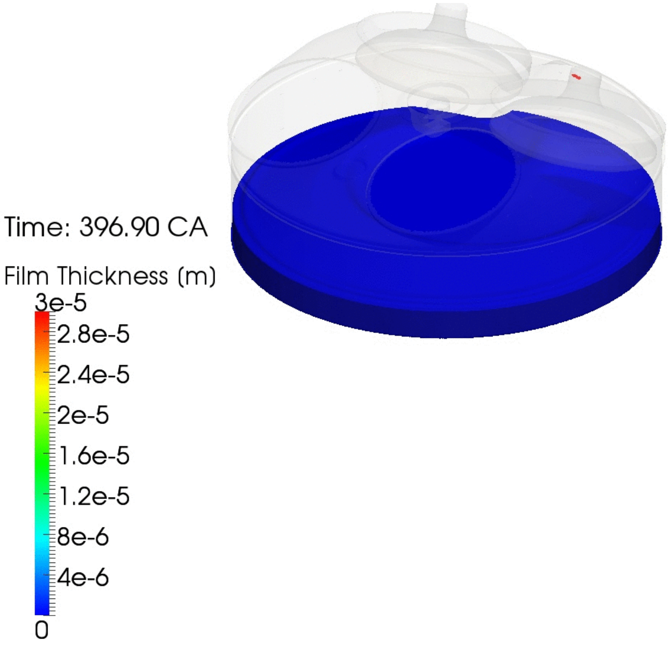
- Flash boiling condition: larger spray cone





SI Engines: GDI air-fuel mixing

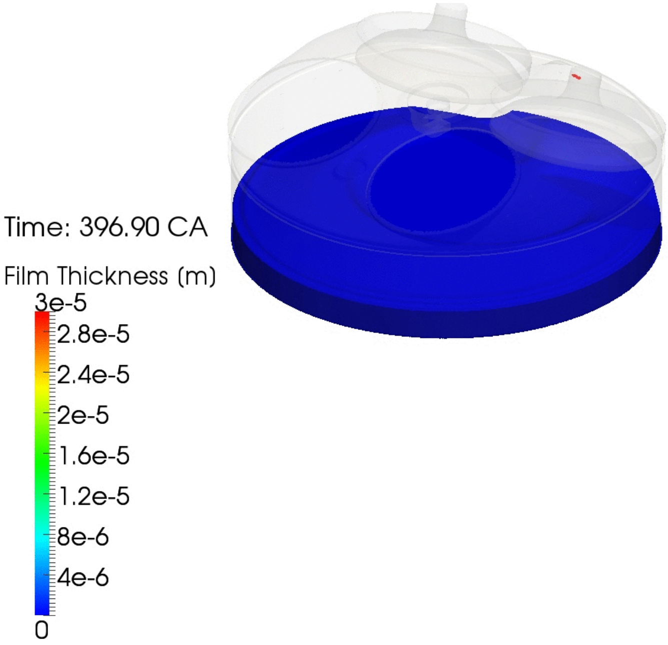
1.0 liter, 3 cyl. VVA engine – Full load condition: fuel balance

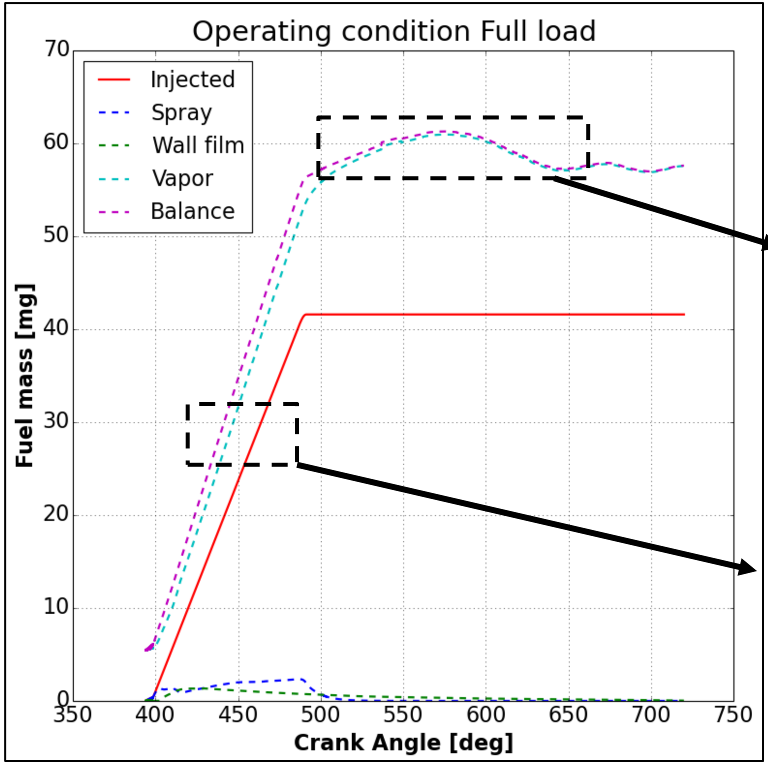


- ➢ **Second order numerical schemes: high in-cylinder TKE**

SI Engines: GDI air-fuel mixing

1.0 liter, 3 cyl. VVA engine – Full load condition: fuel balance

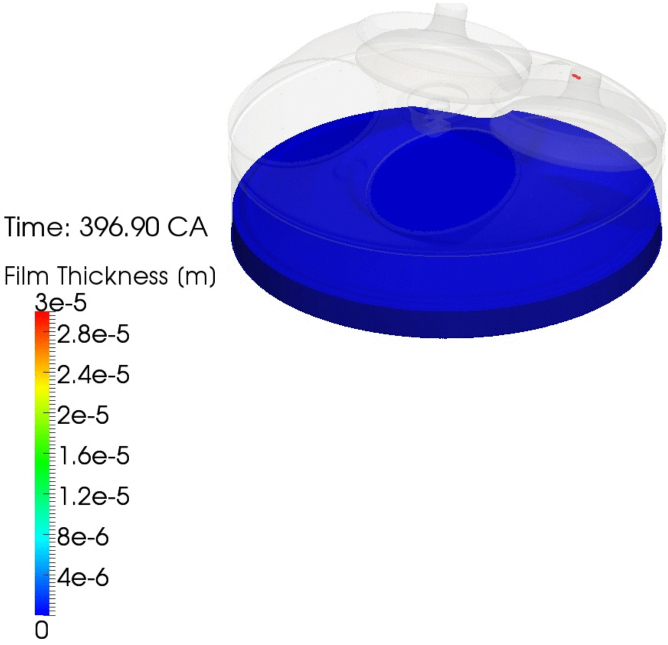




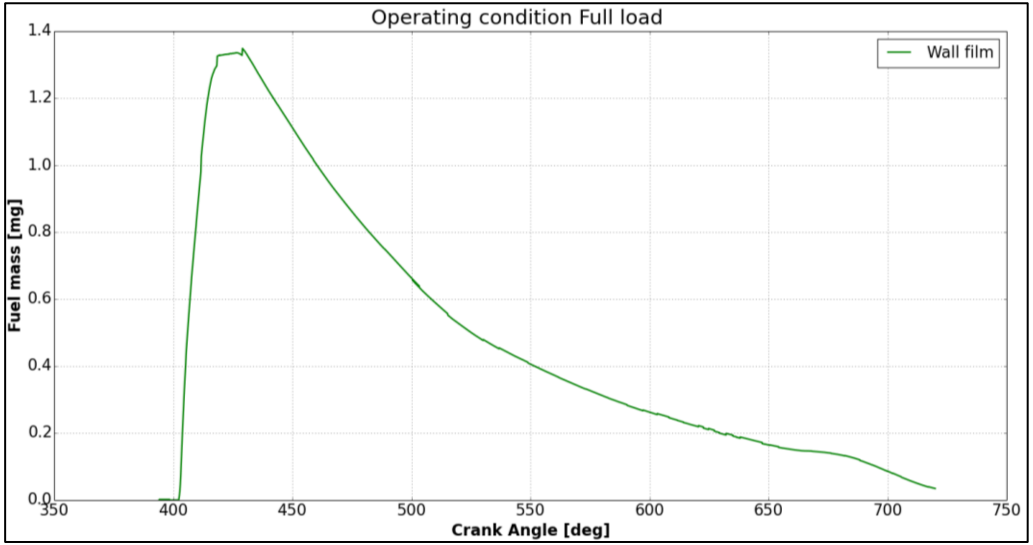
- Accurate global fuel balance
- Oscillations due to fuel backflow in the intake ducts
- Fuel initialization in the intake ducts

SI Engines: GDI air-fuel mixing

1.0 liter, 3 cyl. VVA engine – Full load condition: fuel balance

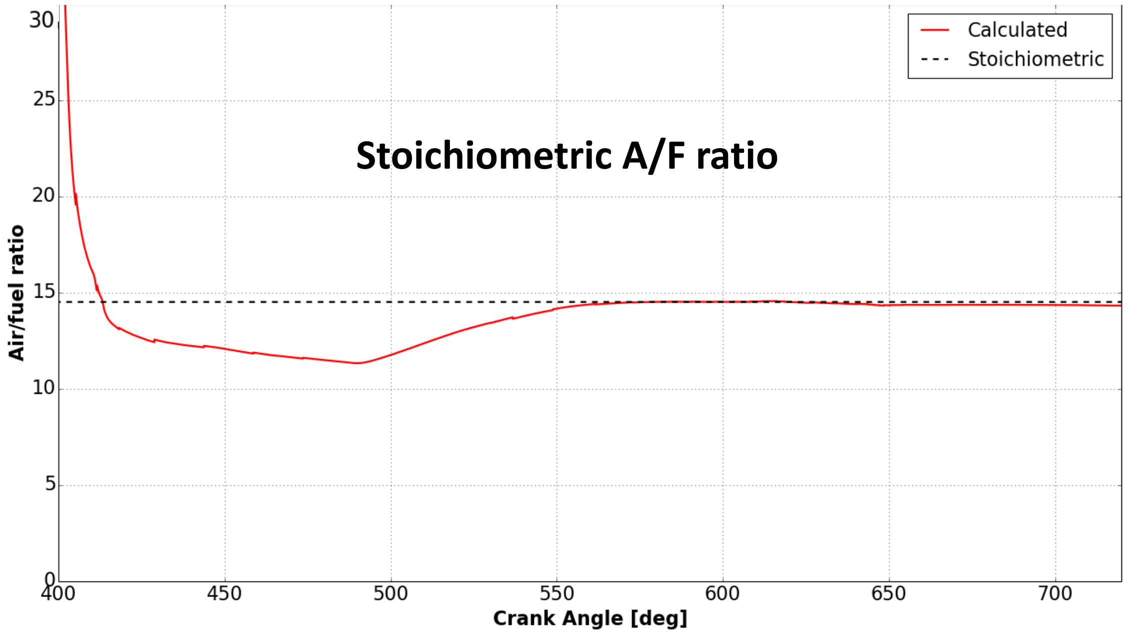


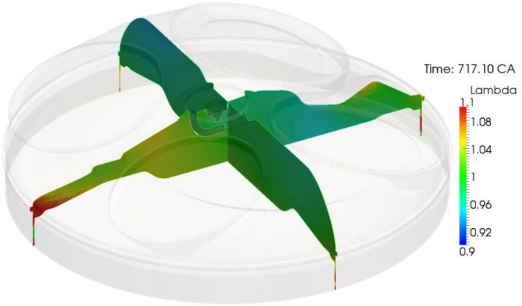
- **Complete wall-film evaporation**

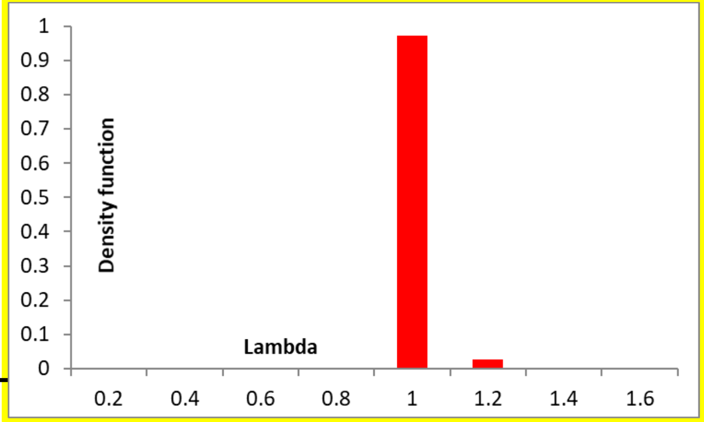


SI Engines: GDI air-fuel mixing

1.0 liter, 3 cyl. VVA engine – Full load condition: mixture analysis



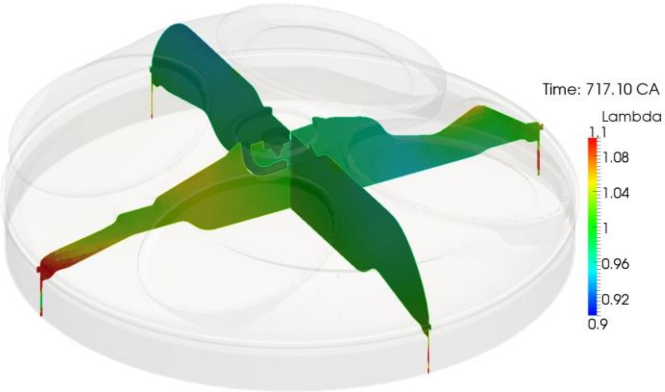




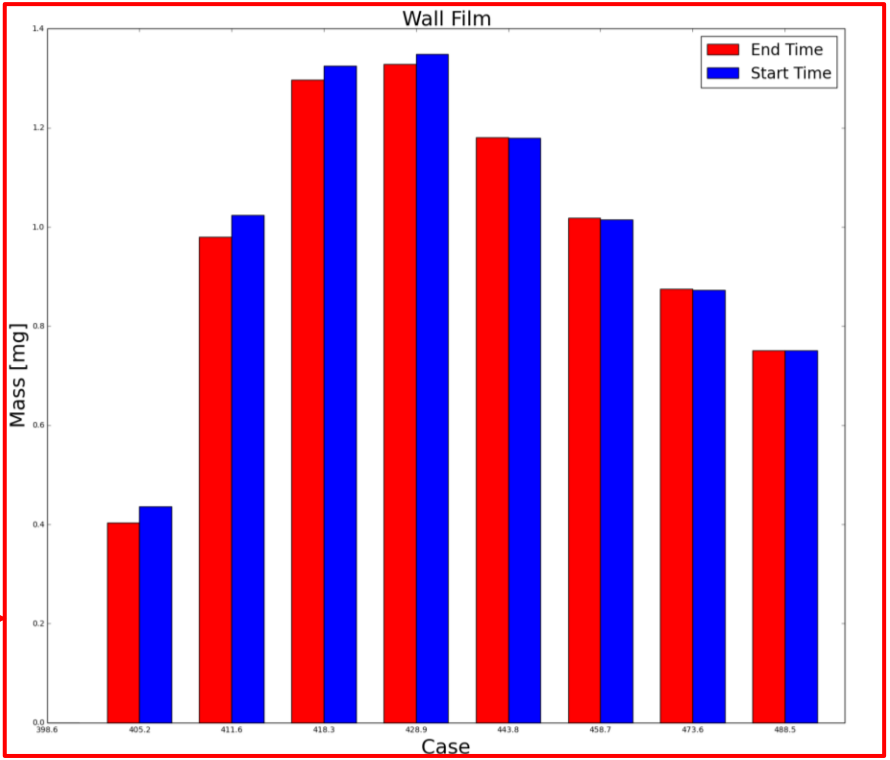
Completely homogeneous mixture condition

SI Engines: GDI air-fuel mixing

1.0 liter, 3 cyl. VVA engine – Full load condition: fuel conservation

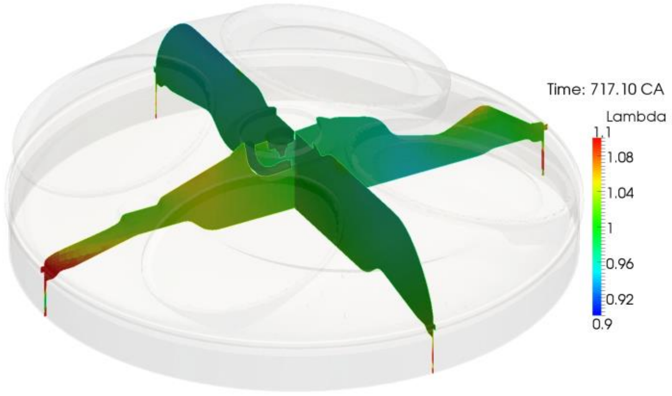


- **Important to ensure consistency of the mesh-to-mesh mapping process. Condition satisfied for:**
  - Wall film

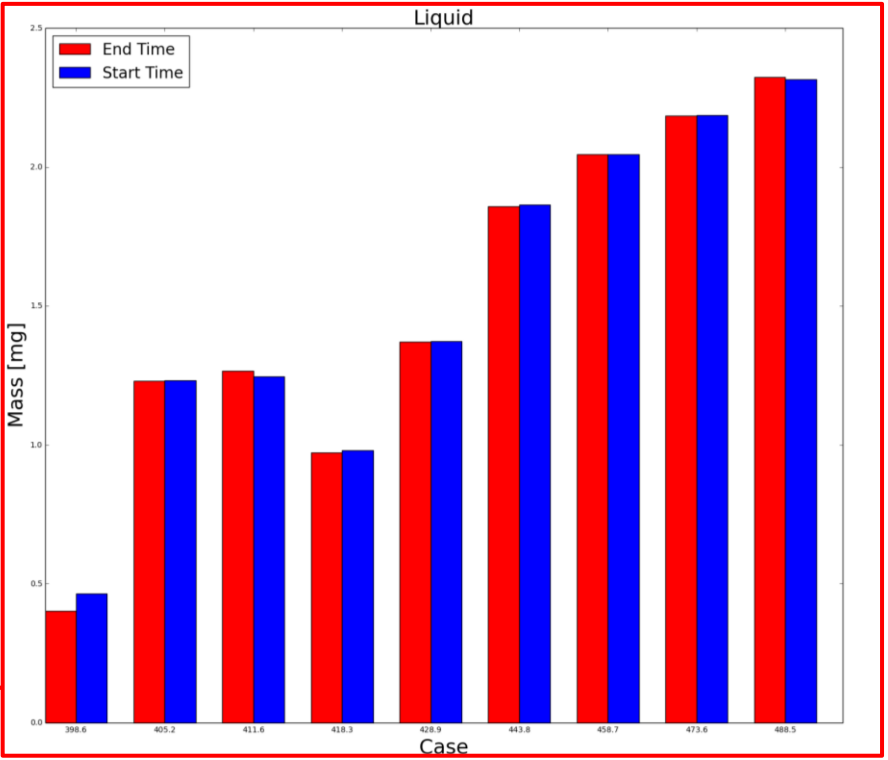


SI Engines: GDI air-fuel mixing

1.0 liter, 3 cyl. VVA engine – Full load condition: fuel conservation

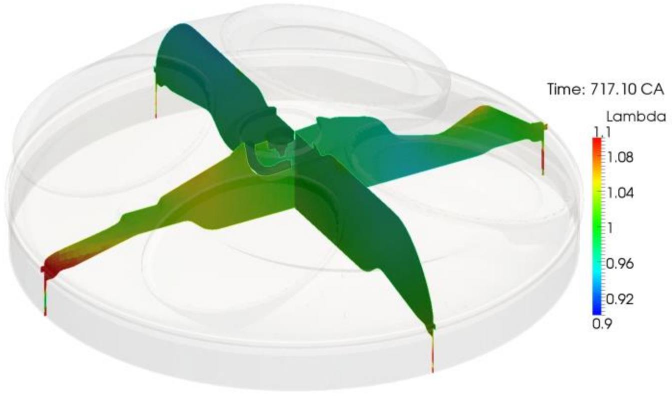


- **Important to ensure consistency of the mesh-to-mesh mapping process. Condition satisfied for:**
  - Wall film
  - Liquid fuel

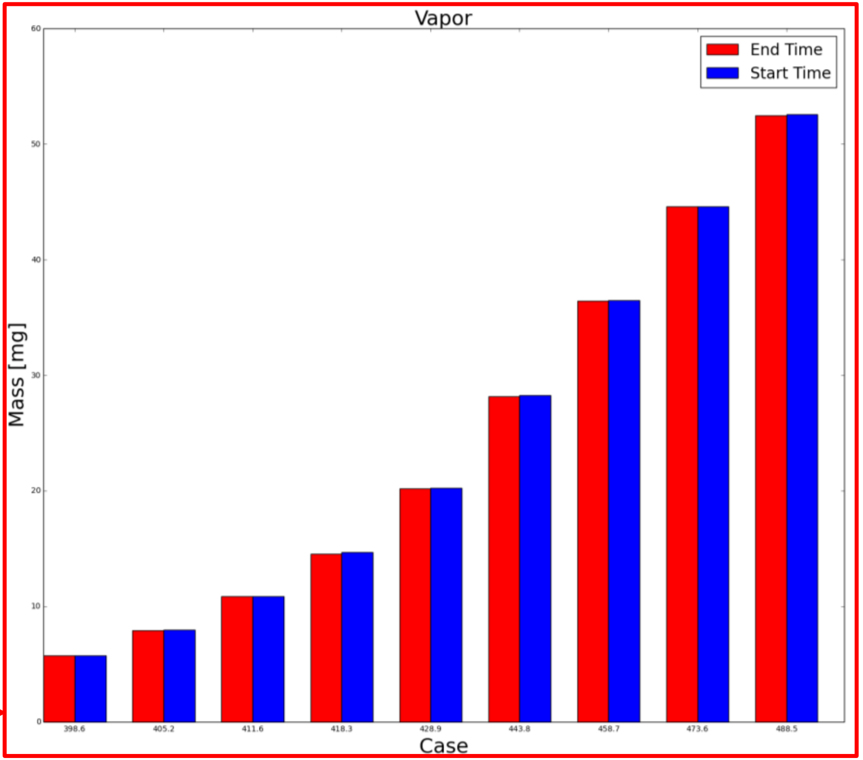


SI Engines: GDI air-fuel mixing

1.0 liter, 3 cyl. VVA engine – Full load condition: fuel conservation

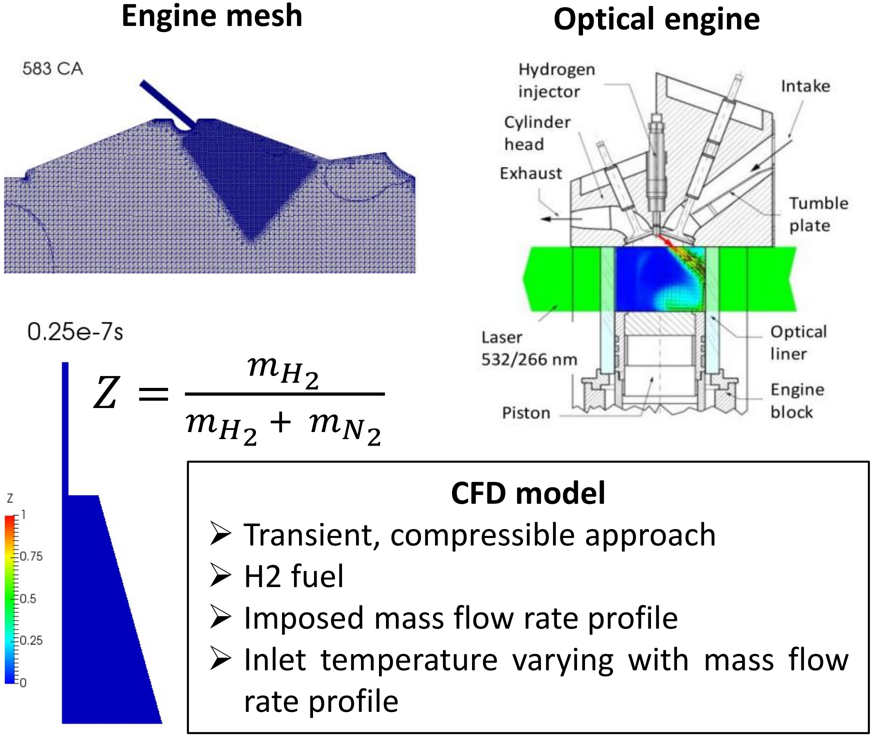


- **Important to ensure consistency of the mesh-to-mesh mapping process. Condition satisfied for:**
  - ❑ Wall film
  - ❑ Liquid fuel
  - ❑ Vapor fuel



SI Engines: natural gas direct injection

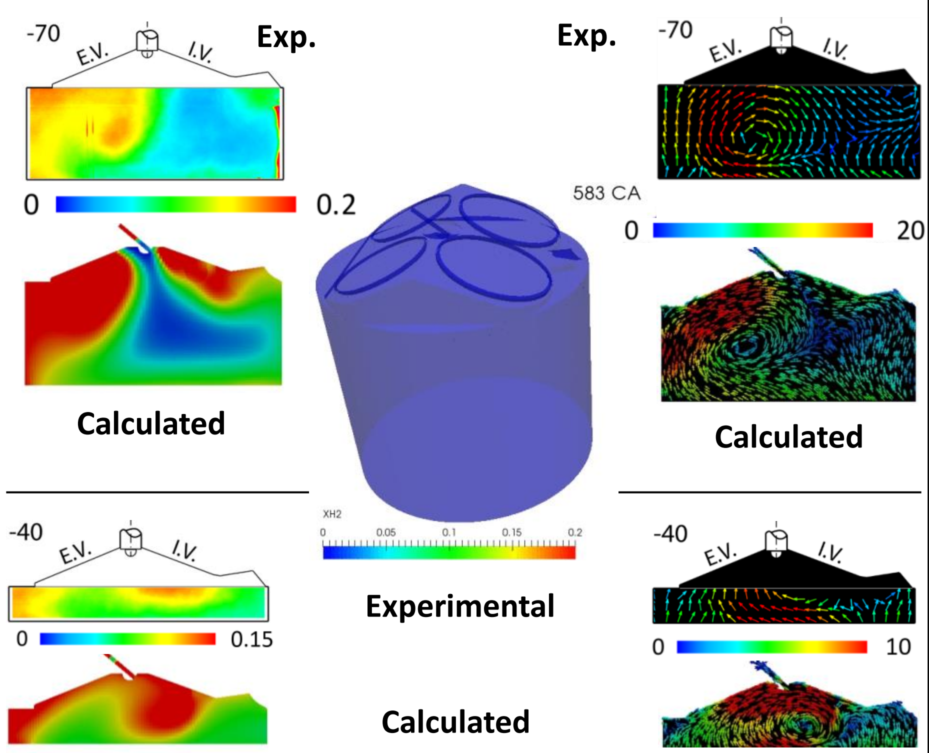
Gaseous direct injection – CFD Model validation on the Sandia optical engine



$$Z = \frac{m_{H_2}}{m_{H_2} + m_{N_2}}$$

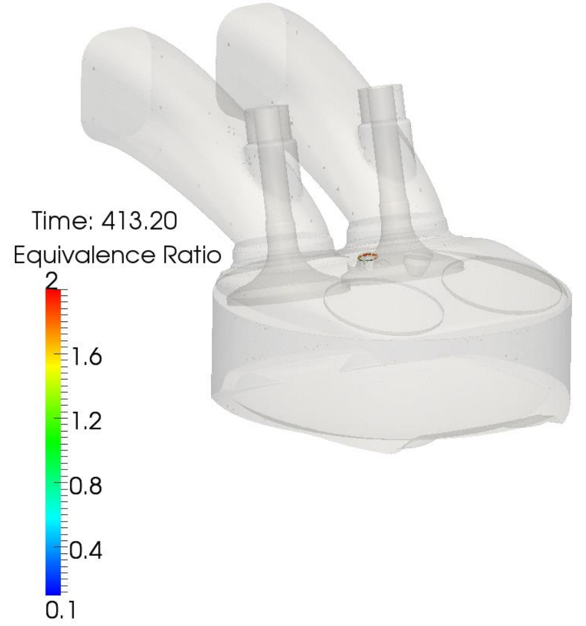
CFD model

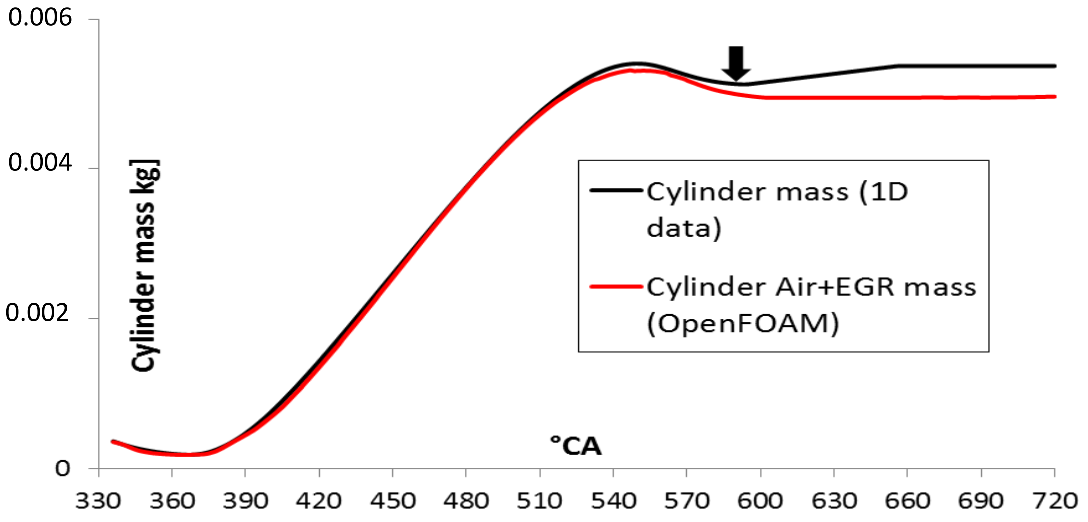
- Transient, compressible approach
- H2 fuel
- Imposed mass flow rate profile
- Inlet temperature varying with mass flow rate profile



SI Engines: natural gas direct injection

HDGAS European project – 1900 rpm full load condition: mass balance

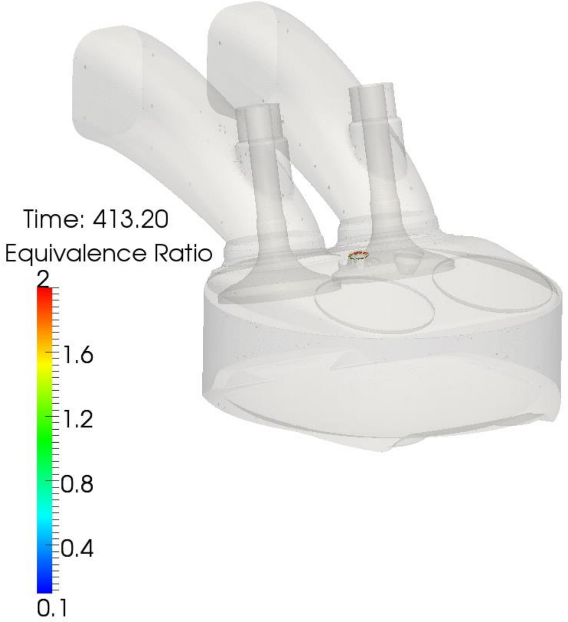


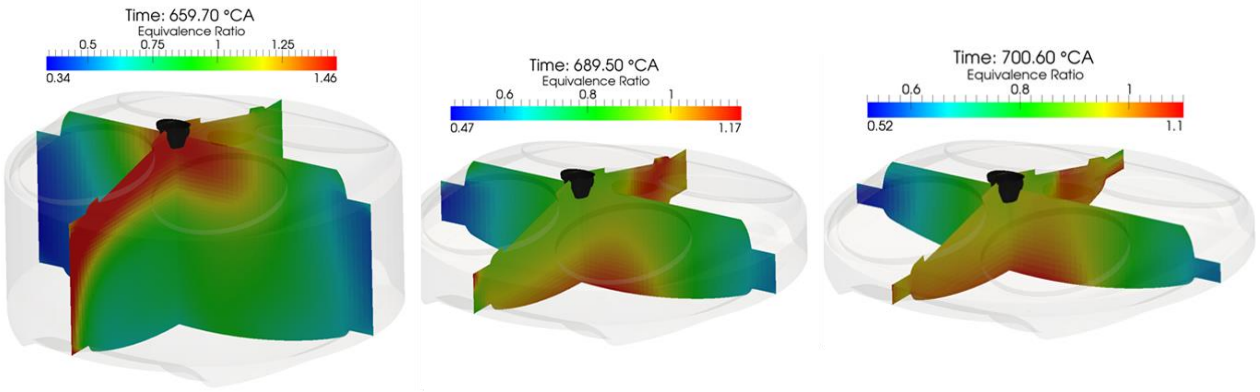


- **3D simulation** allowed to compute **fuel backflow**. **4%** predicted **reduction of required intake air mass** to satisfy the **stoichiometric condition**

SI Engines: natural gas direct injection

HDGAS European project – 1900 rpm full load condition: ER analysis





- **ER ~ 1 close to the spark-plug**: high efficiency of the ignition process
- **Lean zones close to the liner** (unburned HC) and **rich zones near the piston** (CO)

Conclusions and next steps

CFD modeling of in-cylinder phenomena at PoliMi with OpenFOAM

- Consolidated methodologies in gas exchange, injection modeling and air-fuel mixing currently applied in the context of industrial collaborations

Next steps

- Simulation of the combustion process for the different operating points of the 1.0 liter, 3 cyl. VVA engine
- GDI multi-hole spray modeling in vessel:
  - SMD injection with Rosin-Rammler distribution
  - Better reproduce the effects due to plume to plume interaction
  - More detailed analysis of the flash boiling condition

Thanks for your attention!