*Fourth Two-Day Meeting on Internal Combustion Engine Simulations Using OpenFOAM Technology, 13-14 February 2020, Department of Energy, Politecnico di Milano*

POLITECNICO MILANO 1863

ICE GROUP POLITECNICO DI MILANO

# *CFD methodologies for the modeling and the design of modern GDI engines and injector geometries*

**D. Paredi**, T. Lucchini, G. D'Errico

Politecnico di Milano, Department of Energy

# Outline

- Numerical framework
- Focus on SI engines applications
  - Full-cycle mesh generation
  - GDI in-vessel spray research and modeling
  - GDI engines simulations and design
- Conclusions

POLITECNICO MILANO 1863

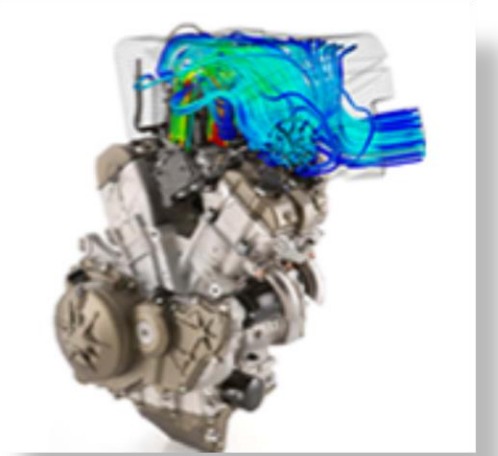
DIPARTIMENTO DI ENERGIA

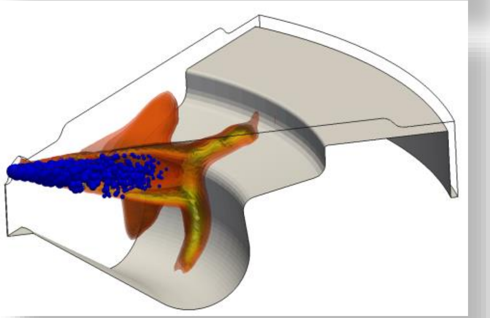
ICE GROUP POLITECNICO DI MILANO

# Introduction

## Why CFD for internal combustion engines?

- Detailed analysis of injection and combustion processes
- Control of pollutant formation to help meet the continuously stricter emission regulations

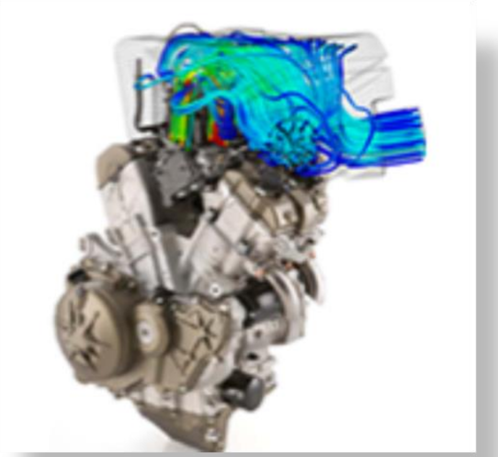




# Introduction

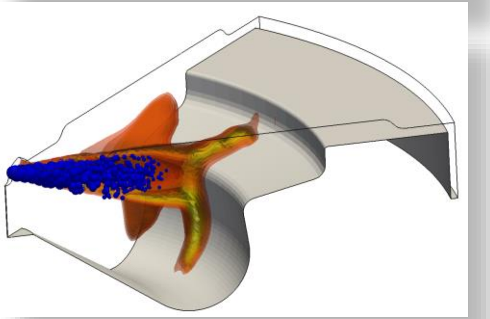
## Why CFD for internal combustion engines?

- Detailed analysis of injection and combustion processes
- Control of pollutant formation to help meet the continuously stricter emission regulations



Spark-Ignition (SI) engines: focus on gasoline direct injection process and mixture formation

- **In-vessel optimization** of spray setup
- **Validation** of the proposed setup in the context of research and industrial projects for the design of **modern, state of the art engines**



# Why OpenFOAM?

## Requirements

Implementation of new models
- Research on fundamental topics
- Extensive validation using different type of data (engine, vessels)

Fully integrated methodologies

Massive application in research and industrial projects

## OpenFOAM is the solution

- Free and opensource
- Many pre-implemented capabilities: meshing, numerics, models
- Different available versions but very compatible
- Perfect basis to develop own libraries and solvers for complex problems

# Numerical framework: the LibICE

Internal combustions engines (ICE) modeling using the open-source OpenFOAM technology

**OpenFOAM**

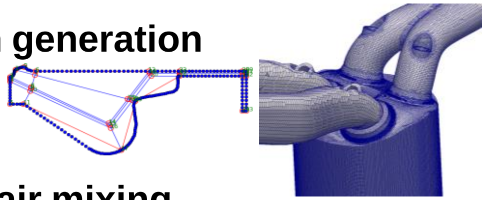
↓

**LibICE**

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

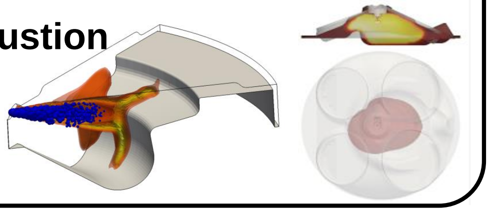
## Engine simulation workflow

### Mesh generation

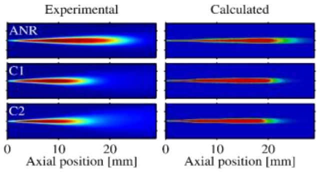


### Fuel-air mixing

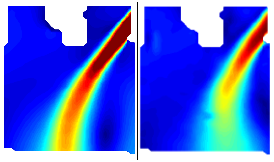
### Combustion



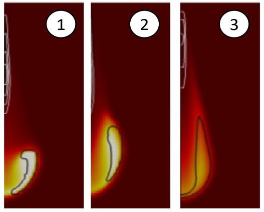
## Development



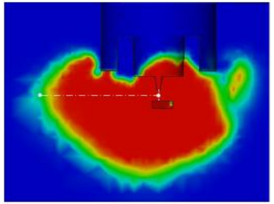

### Spray modeling



### Engine flows




### Diesel combustion



### SI combustion

# Numerical framework: the LibICE

Internal combustions engines (ICE) modeling using the open-source OpenFOAM technology

**OpenFOAM**

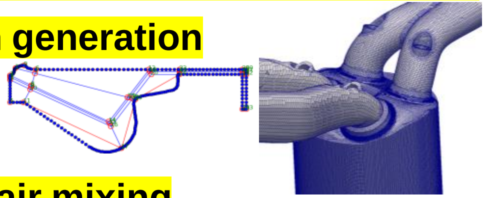
↓

**LibICE**

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

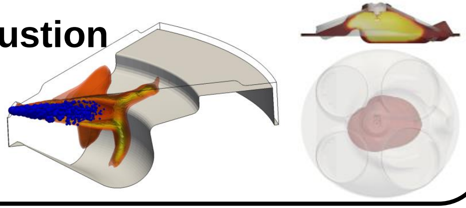
## Engine simulation workflow

**Mesh generation**

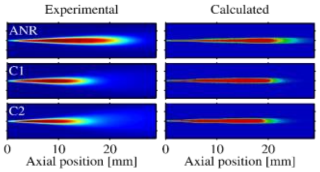


**Fuel-air mixing**

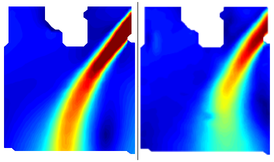
**Combustion**



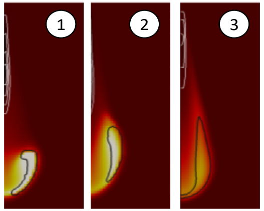
## Development



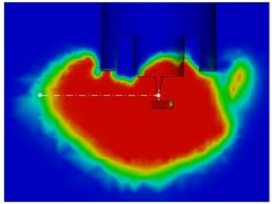

**Spray modeling**



**Engine flows**




**Diesel combustion**



**SI combustion**

# SI engines: main research workflow

**SI engines**

**Mesh management**
- Automatic mesh generation
- Mesh motion/quality
- Topological changes

**Cold flow**
- Discretization
- Turbulence models
- Charge motions

**Air-fuel mixing**
- Lagrangian spray
- Sub-models
- Mixture formation

# Mesh generation and management

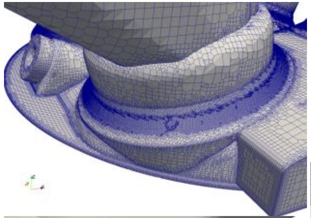
## Global methodology

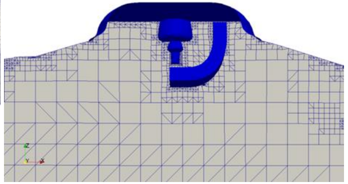
### Full-cycle simulations

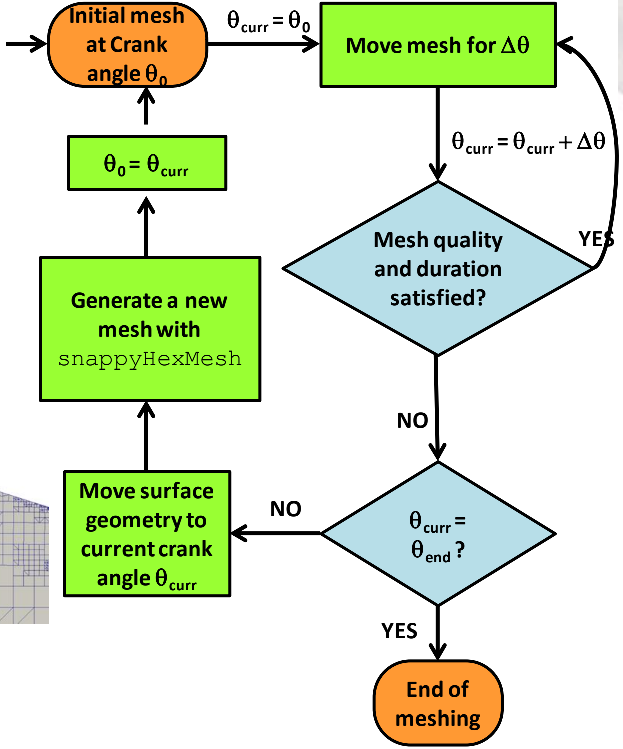
- Multiple meshes
- Mesh to mesh interpolation strategy

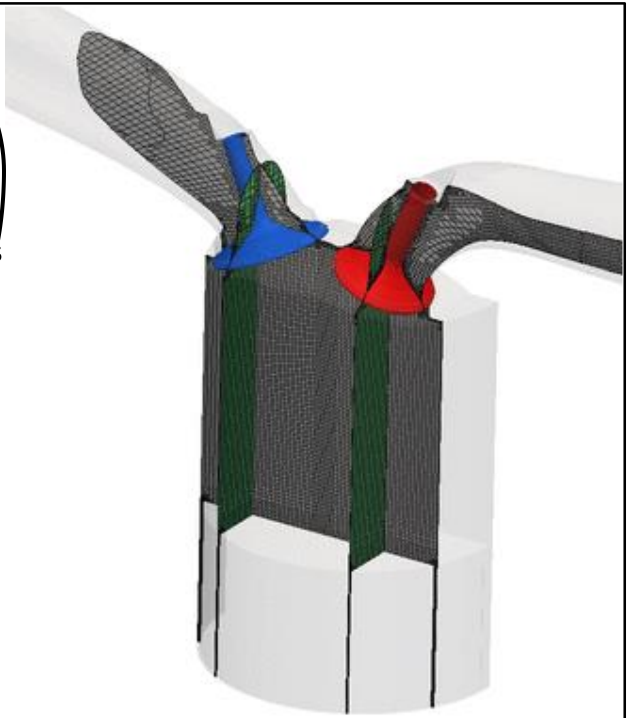
### Duration of each mesh

- User defined + quality criteria





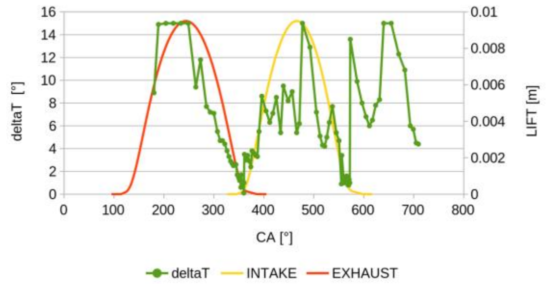


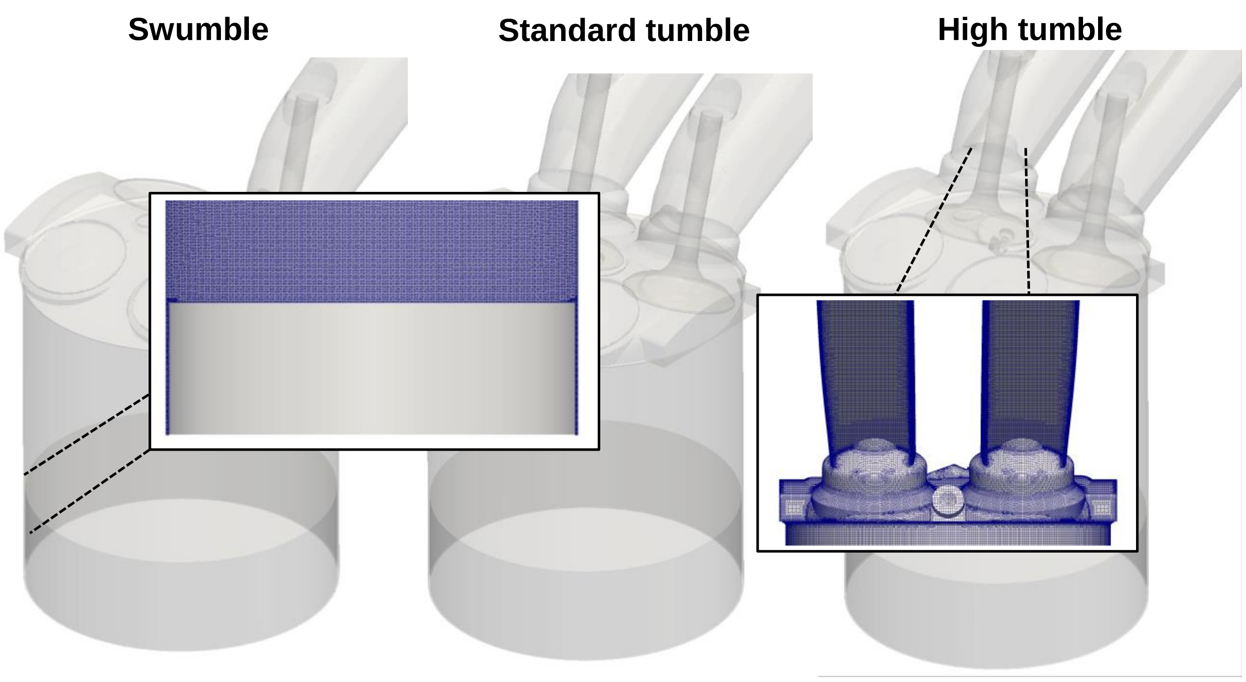



# Mesh generation and management

## Case study: IFP optical engine

| | |
|---|---|
| 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 |
| RPM | 1200 |



# SI engines: main research workflow

## SI engines

### Mesh management

- Automatic mesh generation
- Mesh motion/quality
- Topological changes

### Cold flow

- Discretization
- Turbulence models
- Charge motions

### Air-fuel mixing

- Lagrangian spray
- Sub-models
- Mixture formation

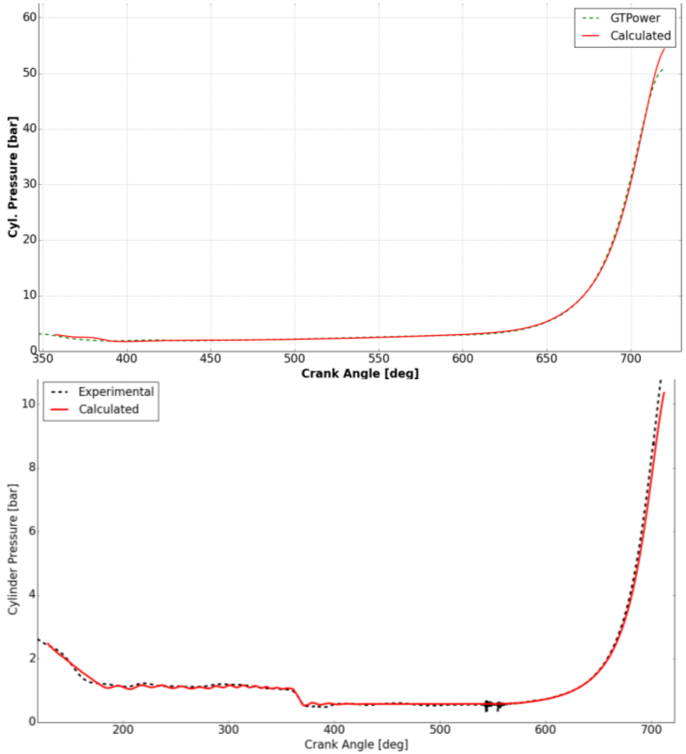
# SI engines: cold flow simulations



## Validation of the numerical approach

### Post-processed fields

- **In-cylinder pressure** (comparison between computed and 1D/experimental data during gas exchange and compression phases)



# SI engines: cold flow simulations

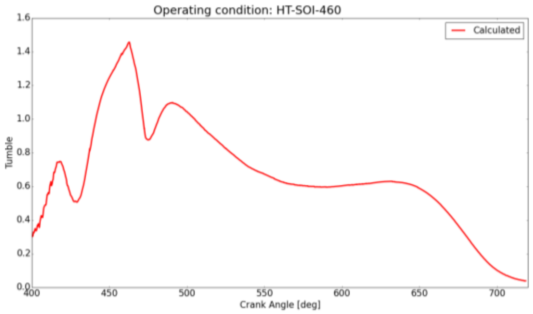


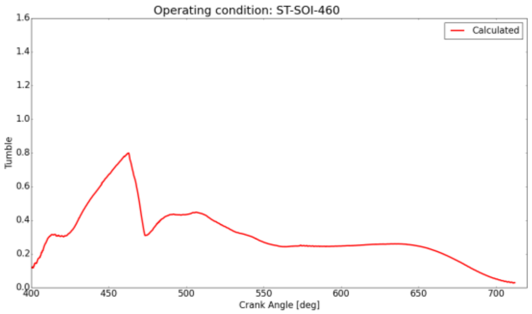
## Validation of the numerical approach

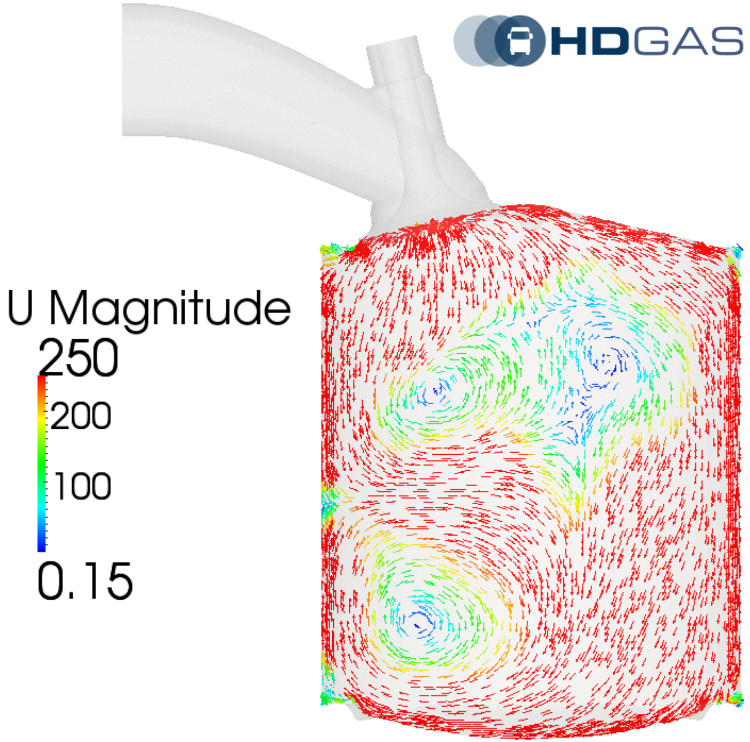
### Post-processed fields

- **In-cylinder pressure** (comparison between computed and 1D/experimental data during gas exchange and compression phases)
- **In-cylinder charge motions**

$$TR = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}(\vec{r}_{i,j} - \vec{r}_c) \times \vec{V}_{i,j}}{\omega \sum_{i=1}^{n}\sum_{j=1}^{m}(\vec{r}_{i,j} - \vec{r}_c) \cdot (\vec{r}_{i,j} - \vec{r}_c)}$$



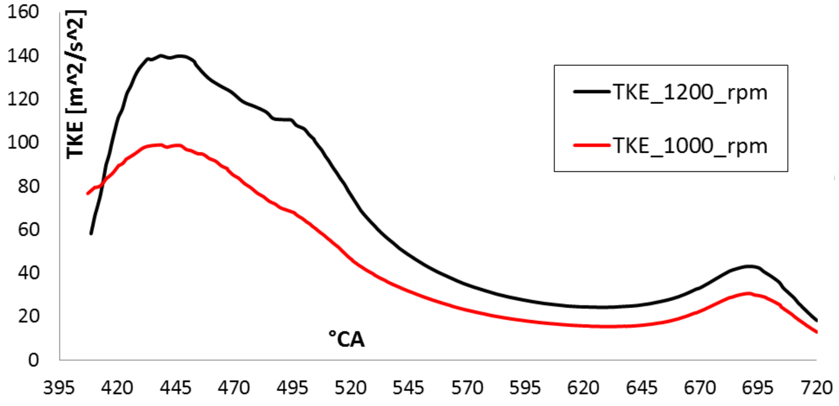
# SI engines: cold flow simulations

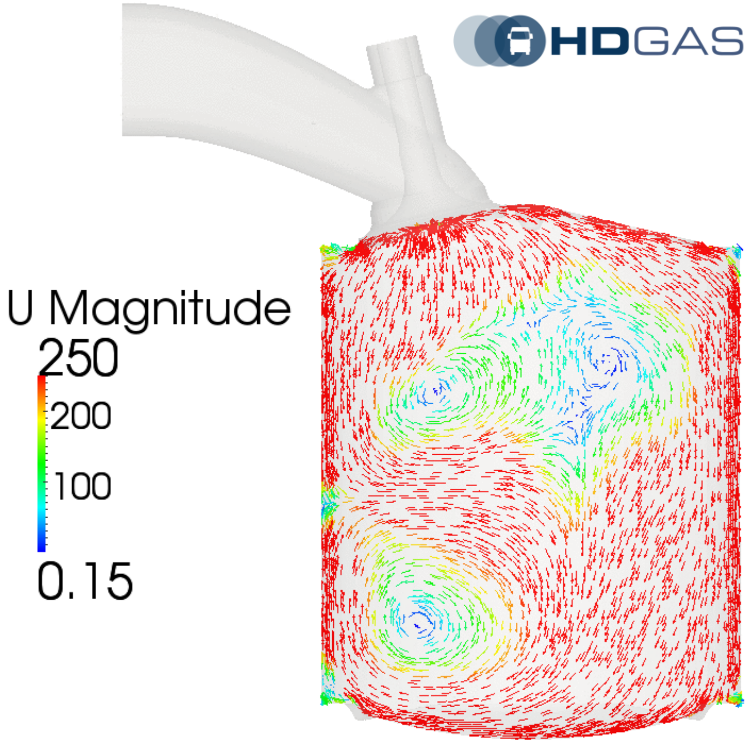
## Validation of the numerical approach

### Post-processed fields

- **In-cylinder pressure** (comparison between computed and 1D/experimental data during gas exchange and compression phases)
- **In-cylinder charge motions**

Effects of rpm on the in-cylinder turbulence intensity



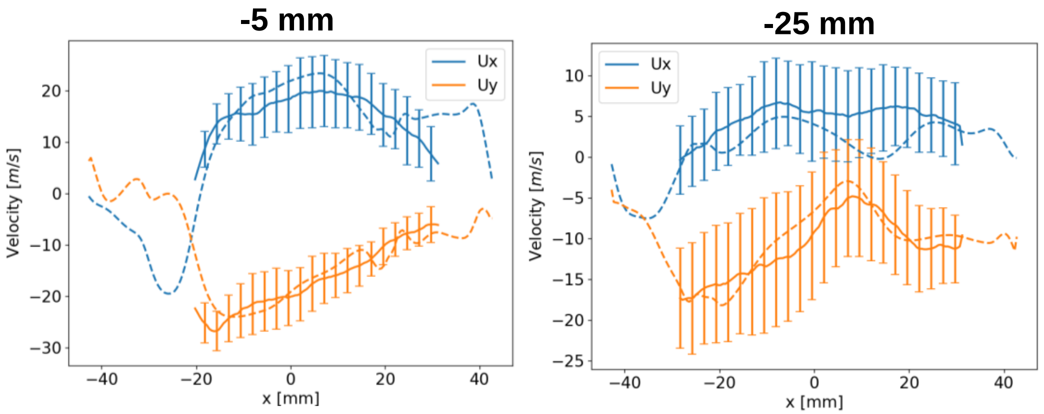



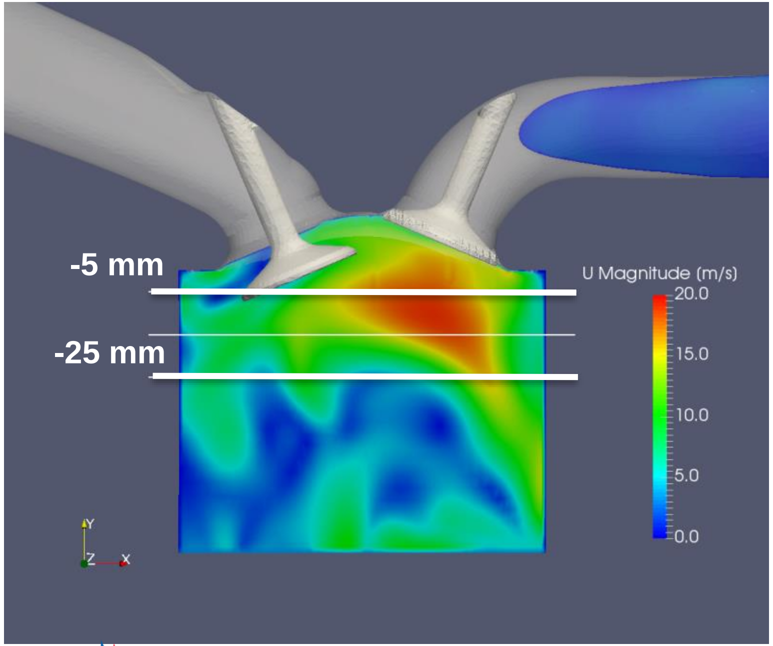
# SI engines: cold flow simulations

## Validation of the numerical approach

### Post-processed fields

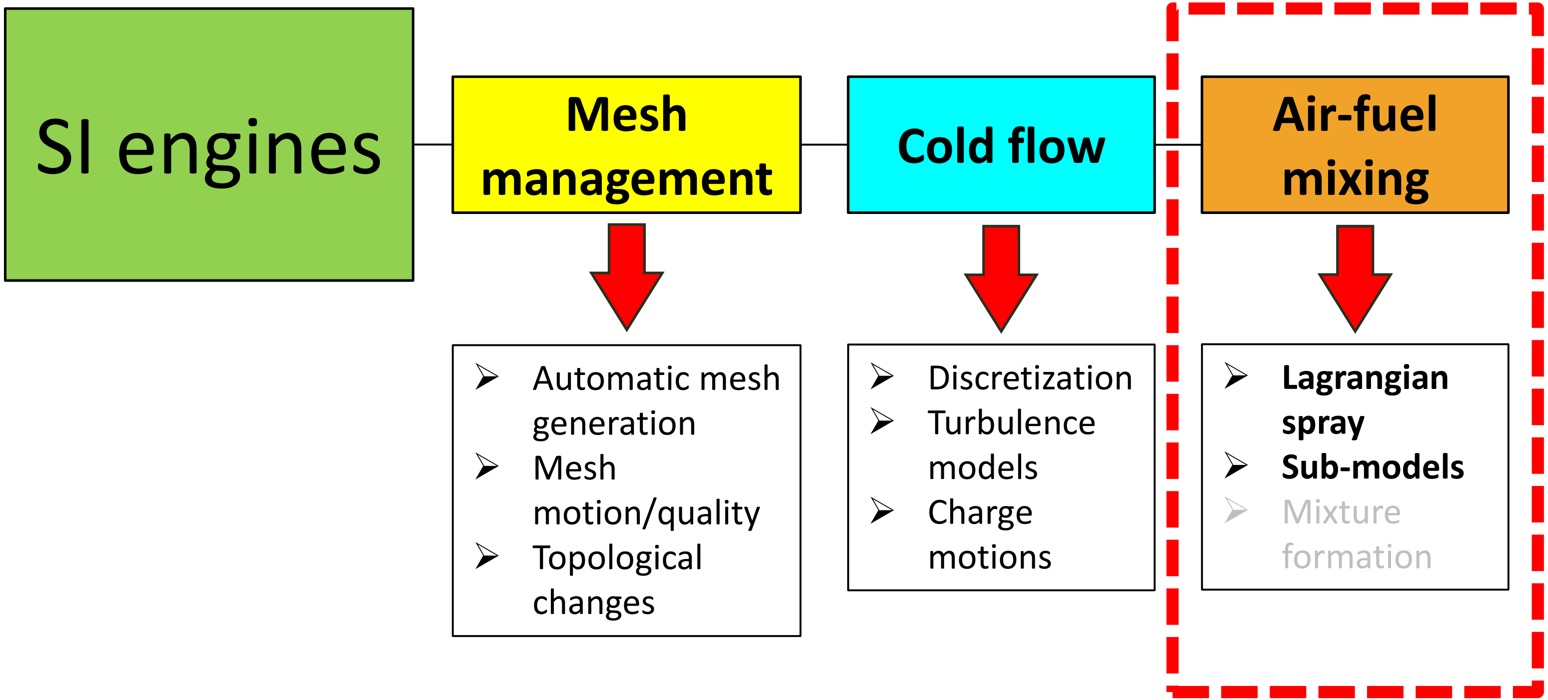
- **In-cylinder pressure** (comparison between computed and 1D/experimental data during gas exchange and compression phases)
- **In-cylinder charge motions (PIV, TU Darmstadt ICE)**




STFS Simulation reaktiver Thermo-Fluid Systeme
POLITECNICO MILANO 1863 DIPARTIMENTO DI ENERGIA
ICE GROUP POLITECNICO DI MILANO

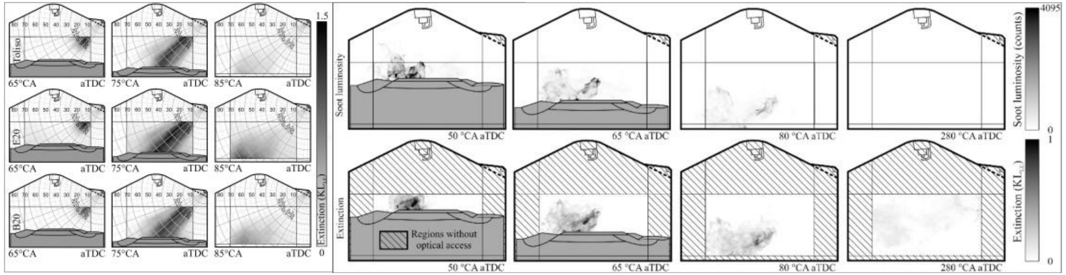
# SI engines: main research workflow



# Lagrangian GDI spray modeling

## Background of the research

**The control of the fuel-air mixing** is an essential component of a gasoline engine design for:
- combustion efficiency
- pollutants formation (mainly soot)



*Spray evolution and associated soot luminosity (Koegl et al., Applied Energy, 2018)*

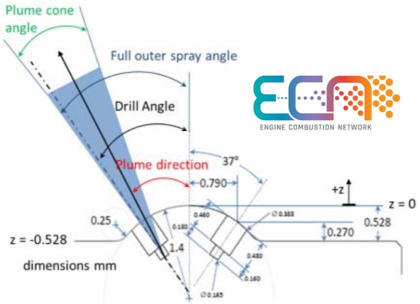
**A trend towards the use of Gasoline Direct-Injection (GDI) has been established**, with improvements in:
- cold-start performance
- knock tendency
- overall thermal efficiency

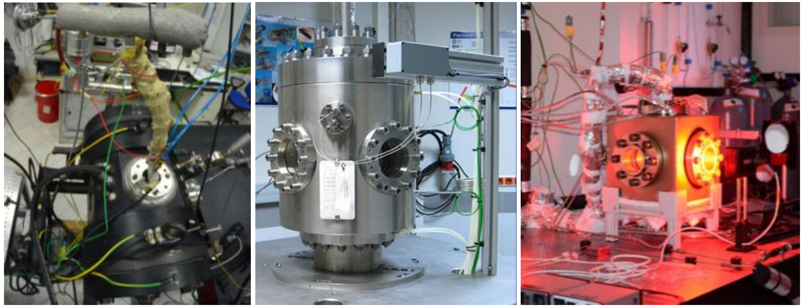
**Further improvements and shortened design cycles** could be achieved by carrying out **computational fluid dynamics (CFD)** simulations

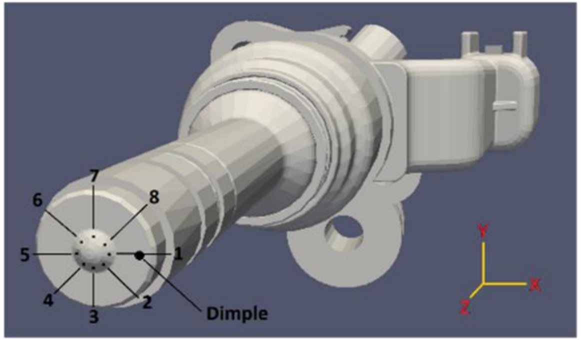
# Lagrangian GDI spray modeling in a static vessel

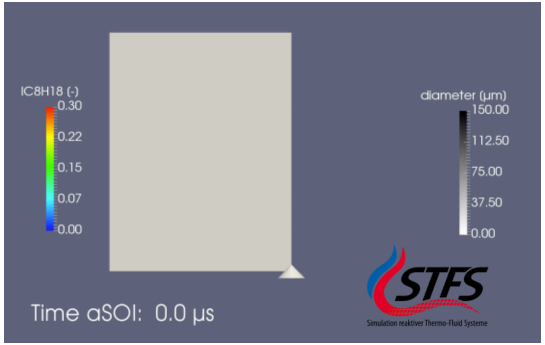
## The reference injector geometry: ECN Spray G

Eight-hole GDI injector manufactured by Delphi and made available by the Engine Combustion Network (ECN) both for experimental and numerical investigations






| | |
|---|---|
| **Orifice diameter (specification)** | 0.165 mm |
| **Orifice drill angle** | 37° relative to the nozzle axis |
| **Fuel** | Iso-octane |
| **Ambient gas** | Pure nitrogen (inert) |
| **Injection pressure** | 200 bar |
| **Fuel temperature** | 363.15 K |
| **Ambient temperature** | 573.15 K |
| **Ambient density** | $3.5\ \frac{kg}{m^3}$ |
| **Injected mass** | 10 mg |
| **Injection duration** | 780 $\mu s$ |

# Lagrangian GDI spray modeling in a static vessel

## The chosen injector geometry: ECN Spray G

Main Spray G operating conditions

| Name | $T_{fuel}$ [K] | $T_a$ [K] | $\rho_a$ [kg/m$^3$] | Ambient pressure [kPa] |
|---|---|---|---|---|
| G1 | 363 | 573 | 3.5 | 600 |
| G2 | 363 | 333 | 0.5 | 50 |
| G3 | 363 | 333 | 1.01 | 100 |
| G7 | 363 | 800 | 9.0 | 2150 |

**Highest evaporating condition:** spray collapse

**Baseline condition,** studied since ECN2 workshop

**Flash boiling condition:** $p_V(T_{fuel}) > p_{amb}$

**Homogeneous operation** of GDI engines with early injection

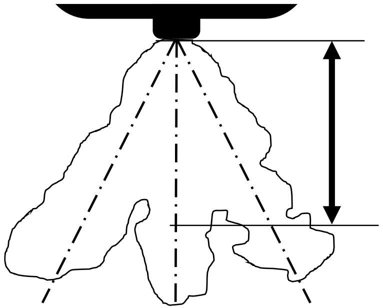
# Lagrangian GDI spray modeling in a static vessel

## Validation of the numerical approach

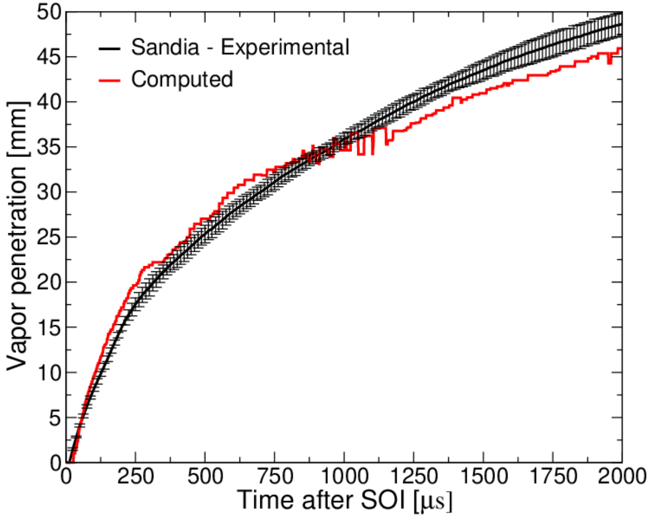
### Post-processed fields

➢ <u>Axial vapor penetration</u>

Computed as the maximum axial distance from the injector nozzle where a mixture fraction of 0.1% is found



**G1**




Sandia National Laboratories

# Lagrangian GDI spray modeling in a static vessel

## Validation of the numerical approach

### Post-processed fields

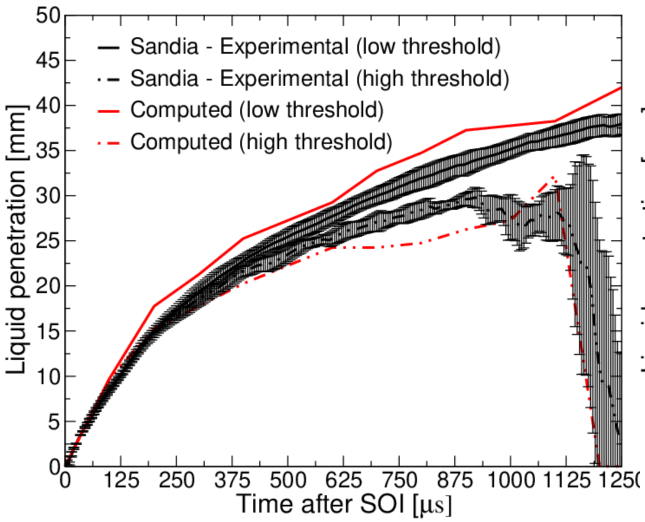
- **Axial liquid penetration**

Since ECN6 Workshop: innovative computation based on double axial threshold of Eulerian Projected Liquid Volume (PLV) field

$$\int_{-y_\infty}^{y_\infty} LVF \cdot dy = 0.2 \cdot 10^{-3} \frac{mm^3 liquid}{mm^2}$$

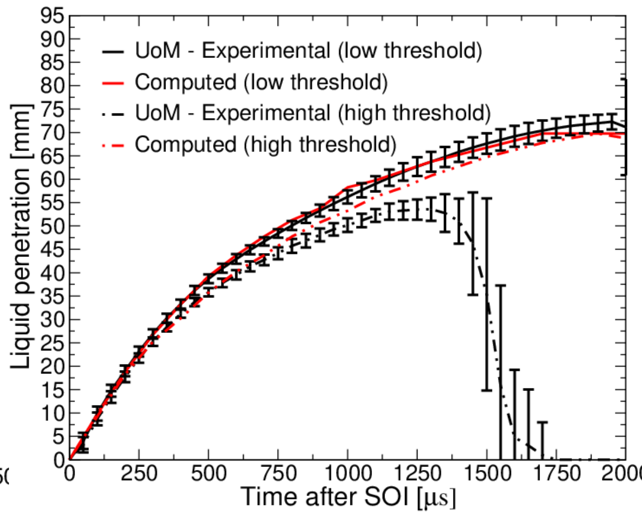
$$\int_{-y_\infty}^{y_\infty} LVF \cdot dy = 2.0 \cdot 10^{-3} \frac{mm^3 liquid}{mm^2}$$

**G1**




Sandia National Laboratories

**G2**




The University of Melbourne

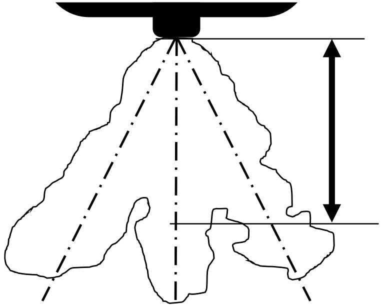
# Lagrangian GDI spray modeling in a static vessel

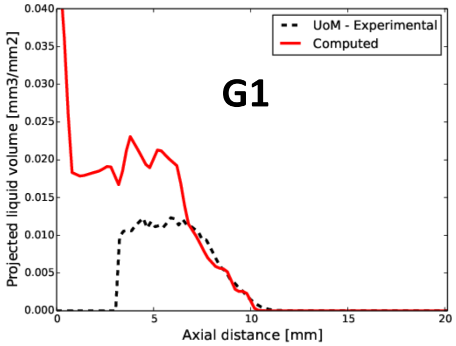
## Validation of the numerical approach

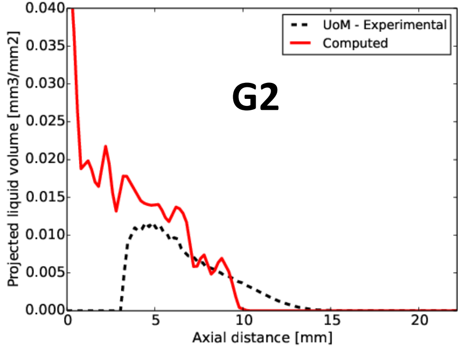
### Post-processed fields

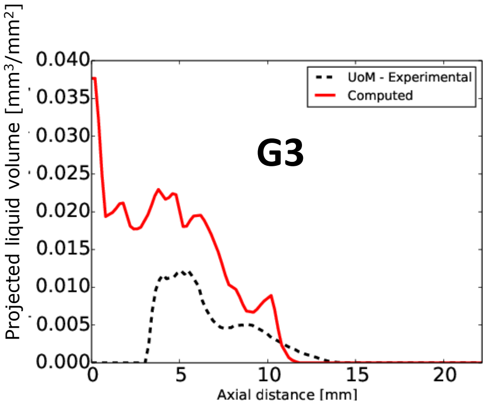
- In-plume liquid distribution

Axial evolution over time of the Projected Liquid Volume (PLV) Eulerian field





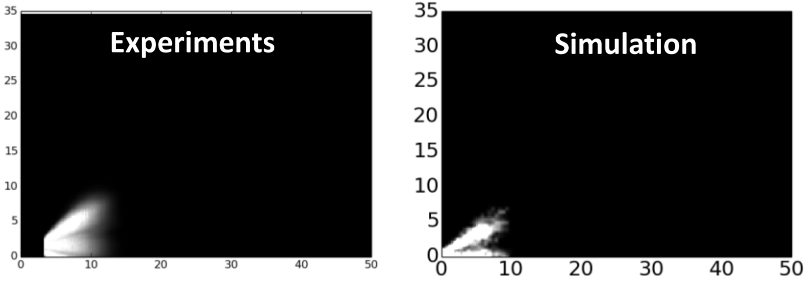




THE UNIVERSITY OF MELBOURNE

$$\tau \frac{\pi d^3/6}{C_{ext}} = \int_{-y_\infty}^{y_\infty} LVF \cdot dy = \int_{-y_\infty}^{y_\infty} \frac{vol.liquid}{unit\ volume} \cdot dy$$

# Lagrangian GDI spray modeling in a static vessel

## Validation of the numerical approach

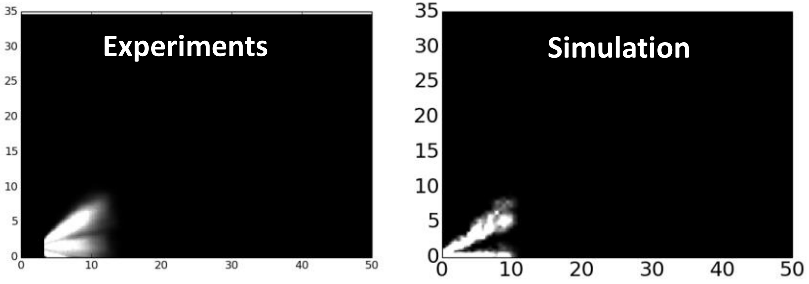



**G2** Range: 0 – 0.01 mm³/mm²

### Post-processed fields

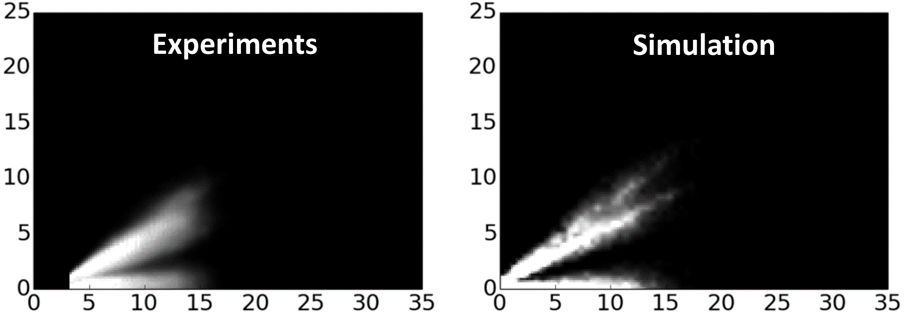
➢ <u>PLV morphology maps</u>

Projected Liquid Volume (PLV) Eulerian field used as a source for a direct comparison over time between experimental and numerical spray morphologies




**G3**

**G1**



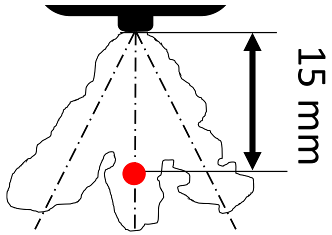
# Lagrangian GDI spray modeling in a static vessel

## Validation of the numerical approach

### Post-processed fields

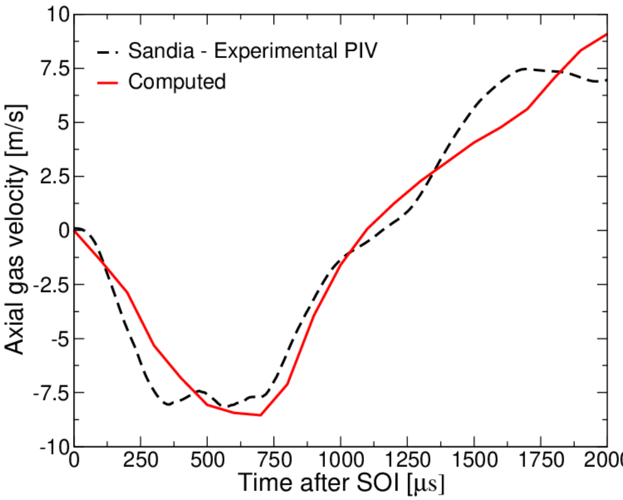
➢ <u>Centerline axial velocity</u>

Axial gas velocity evolution over time evaluated at 15 mm downstream of the injector nozzle. It allows for the assessment of entrainment efficiency



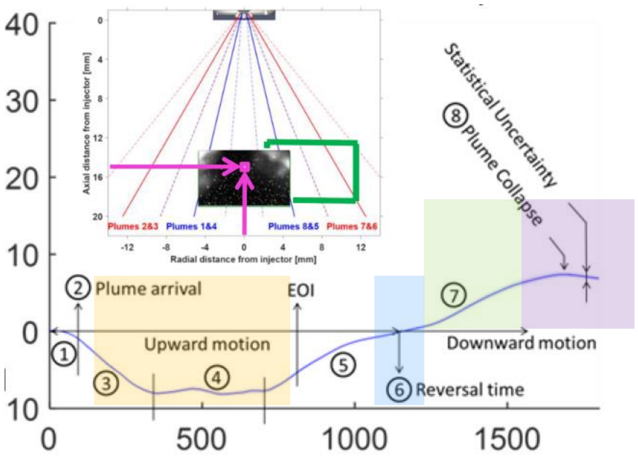

Sandia National Laboratories

**G1**




**Different motion regimes:**

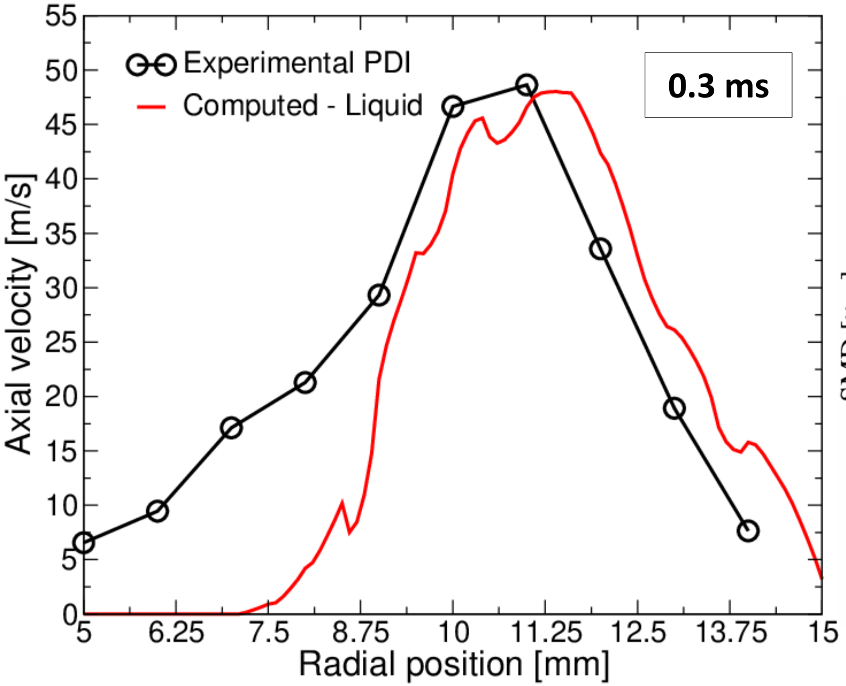
- Upward
- Reversal
- Downward
- Collapse



# Lagrangian GDI spray modeling in a static vessel

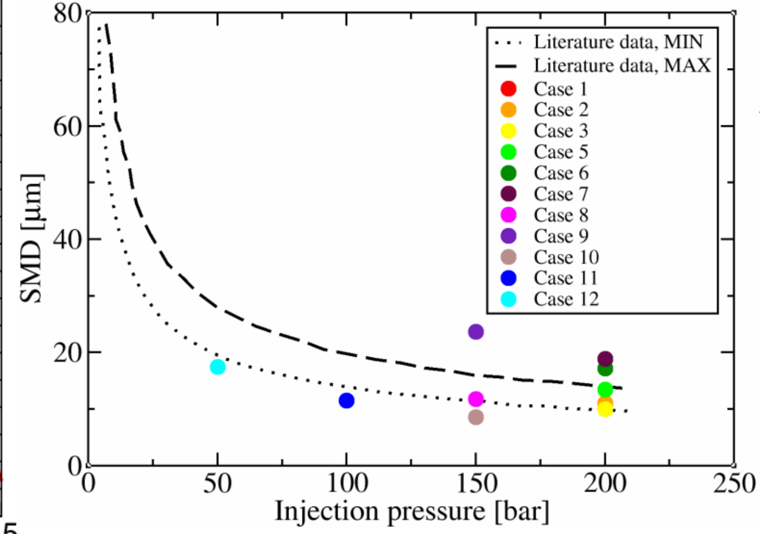
## Validation of the numerical approach

### G1 - PDI




### Post-processed fields

- PDI liquid droplets velocity and SMD




| Case | $p_{inj}$) [bar] |
|---|---|
| Case 1 (ECN) | 200 |
| Case 2 (ECN) | 200 |
| Case 3 (ECN) | 200 |
| Case 4 | 200 |
| Case 5 | 200 |
| Case 6 | 200 |
| Case 7 | 200 |
| Case 8 | 150 |
| Case 9 | 150 |
| Case 10 | 150 |
| Case 11 | 100 |
| Case 12 | 50 |

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

# SI engines: main research workflow

**SI engines**

**Mesh management**
- Automatic mesh generation
- Mesh motion/quality
- Topological changes

**Cold flow**
- Discretization
- Turbulence models
- Charge motions

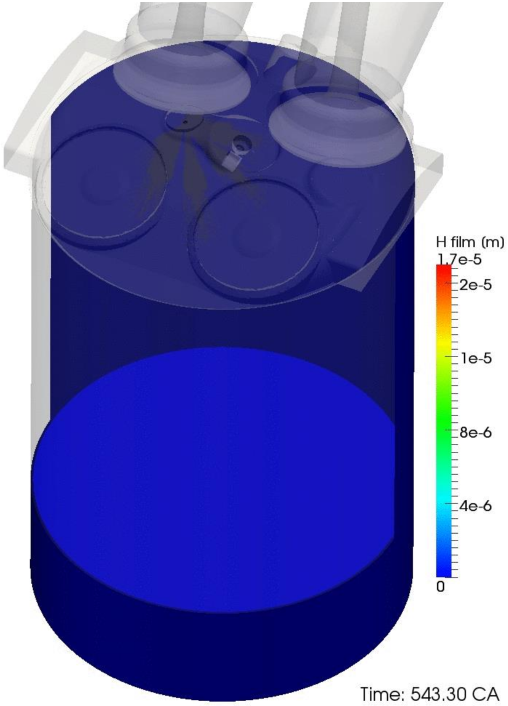
**Air-fuel mixing**
- Lagrangian spray
- Sub-models
- **Mixture formation**

# SI engines: GDI full-cycle simulations

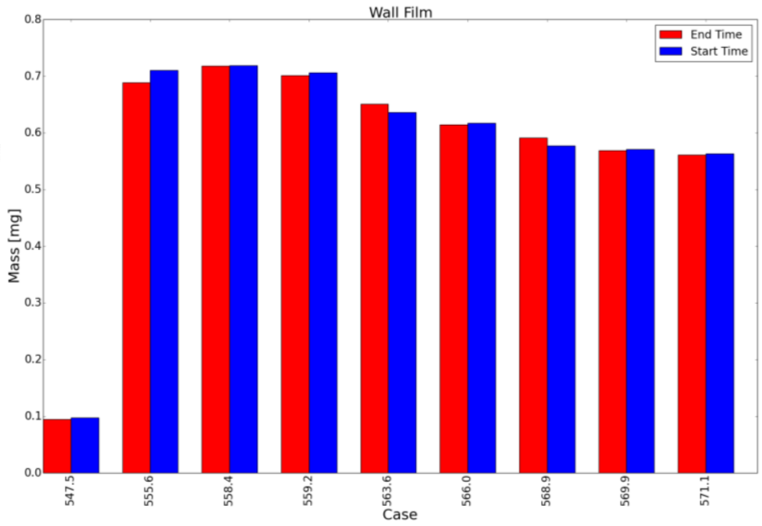
## Numerical validation. Case study: IFP optical engine

### Verification of simulations accuracy

- Conservation of fuel mass from one case to another
- Multiple spray impingement spots on piston and liner




IFP, SOI = 540 CA



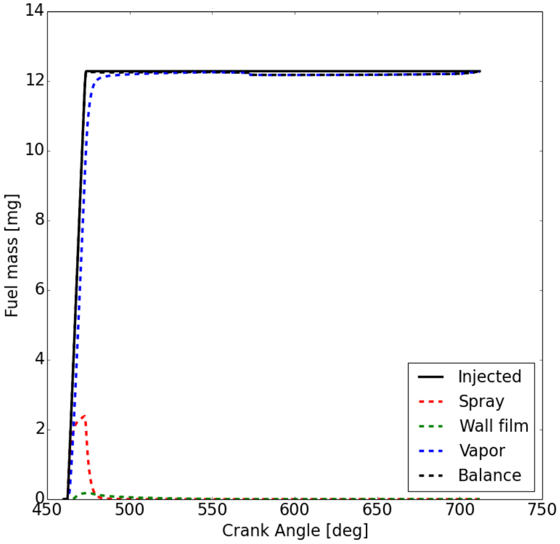
# SI engines: GDI full-cycle simulations

## Numerical validation. Case study: IFP optical engine

**Verification of simulations accuracy**

- Conservation of fuel mass from one case to another
- Multiple spray impingement spots on piston and liner
- Impingement, wall-film evolution (evaporation, stripping) on intake valve
- Overall fuel mass conservation

**IFP, SOI = 460 CA**

# SI engines: GDI full-cycle simulations



## Numerical validation. Case study: IFP optical engine

**SOI = 460 CA**

- **Air-fuel mixing:** effects of in-cylinder flow motion and turbulence on the liquid spray and vice versa

# SI engines: GDI full-cycle simulations

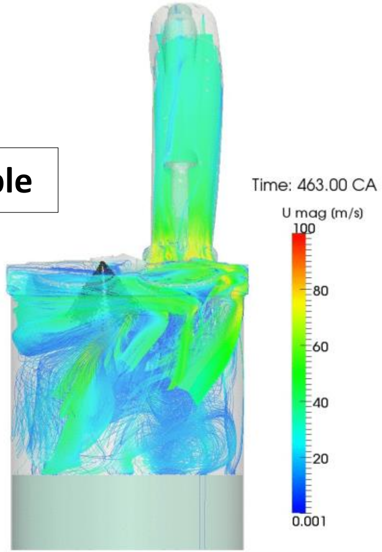


## Numerical validation. Case study: IFP optical engine

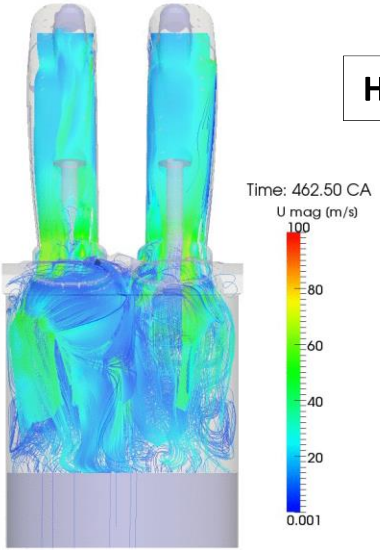
- **Air-fuel mixing:** effects of in-cylinder flow motion and turbulence on the liquid spray and vice versa

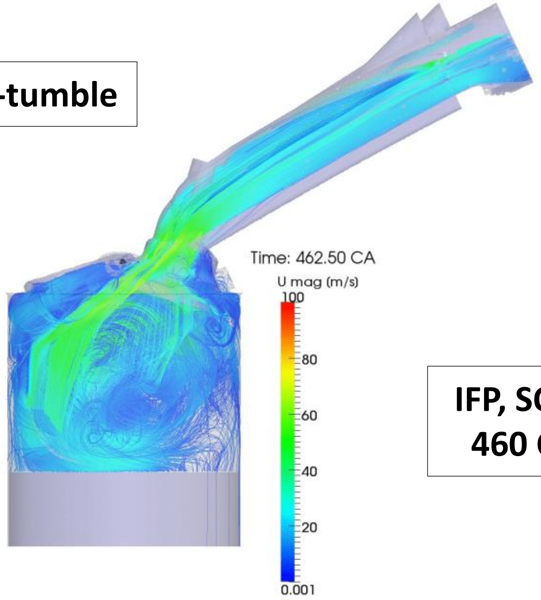
Swumble

IFP, SOI = 460 CA




High-tumble



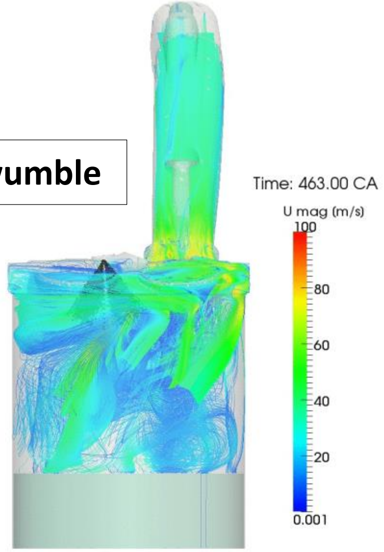

IFP, SOI = 460 CA

# SI engines: GDI full-cycle simulations

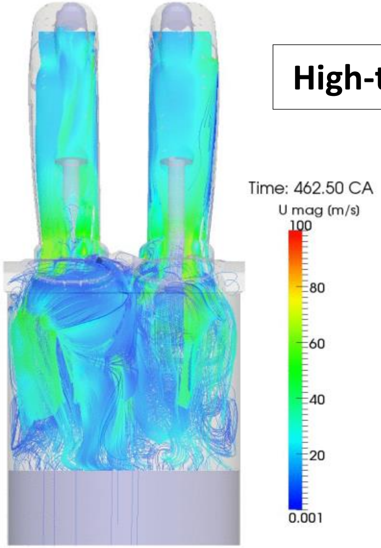
## Numerical validation. Case study: IFP optical engine

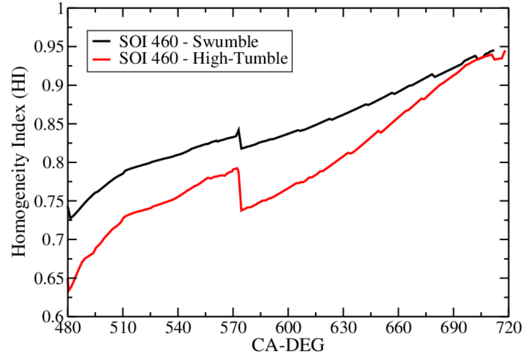
- **Air-fuel mixing:** effects of in-cylinder flow motion and turbulence on the liquid spray and vice versa

**Swumble**



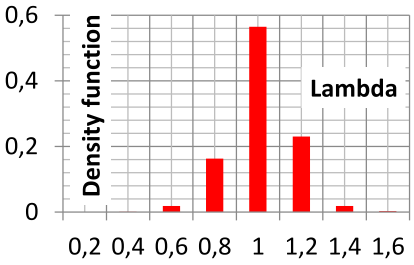

**High-tumble**



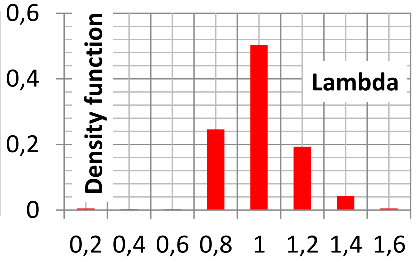




**IFP, SOI = 460 CA**

- Promoted higher mixture homogeneity, on average, by the Swumble configuration




**Swumble, 700 CA**




**High Tumble, 700 CA**

- Similar in-cylinder Lambda density distribution

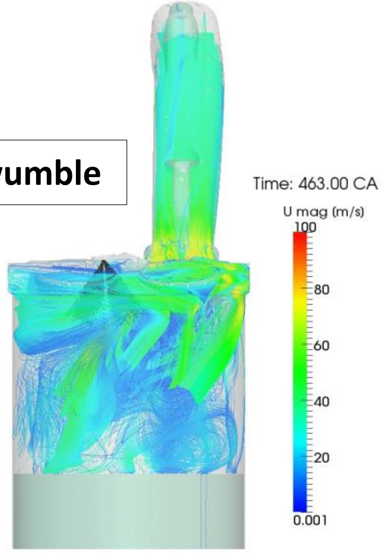
# SI engines: GDI full-cycle simulations



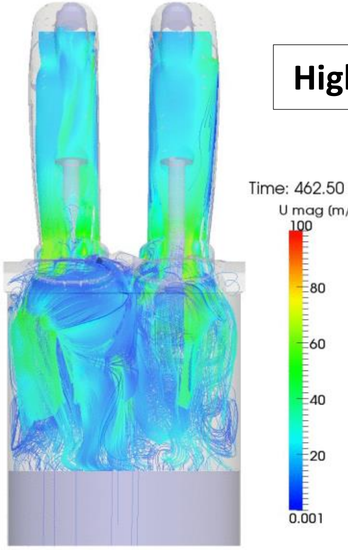
## Numerical validation. Case study: IFP optical engine

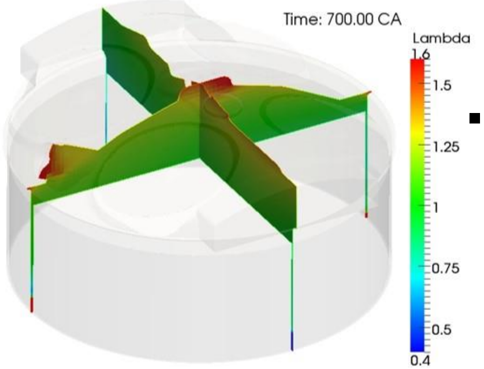
- **Air-fuel mixing:** effects of in-cylinder flow motion and turbulence on the liquid spray and vice versa

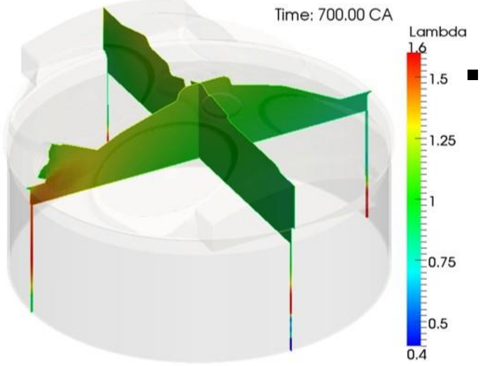
Swumble




High-tumble




**IFP, SOI = 460 CA**

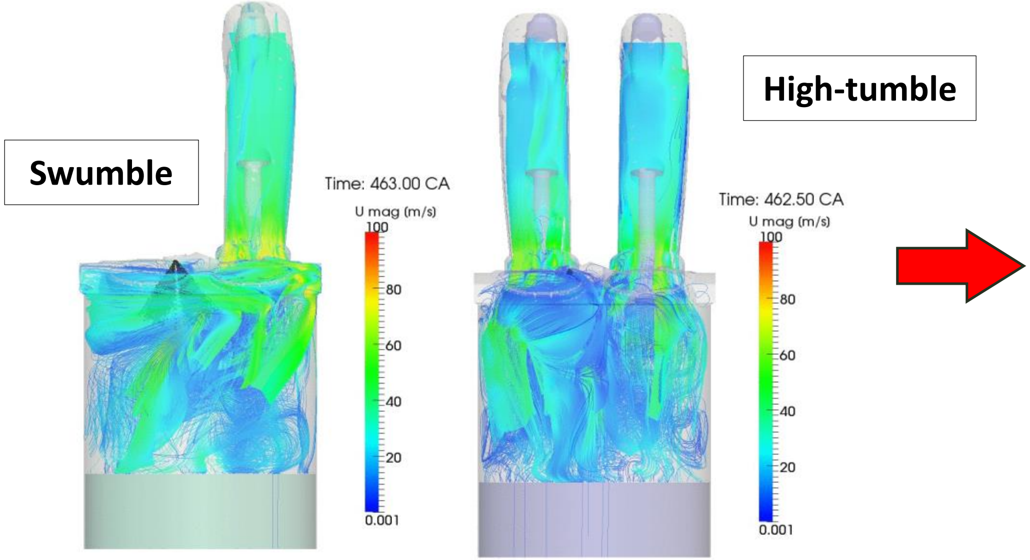
- **Swumble**: lean mixture near the spark-plug and the cylinder-head surface. Rich mixture in the crevices
- **High-Tumble**: mixture closer to stoich. conditions in the chamber. Both lean and rich distributions in the crevices

# SI engines: GDI full-cycle simulations

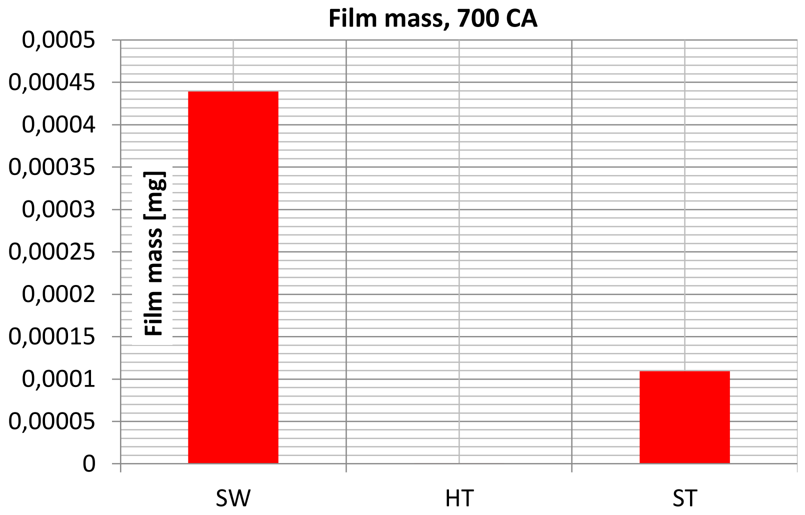


## Numerical validation. Case study: IFP optical engine

- **Air-fuel mixing:** effects of in-cylinder flow motion and turbulence on the liquid spray and vice versa




**IFP, SOI = 460 CA**



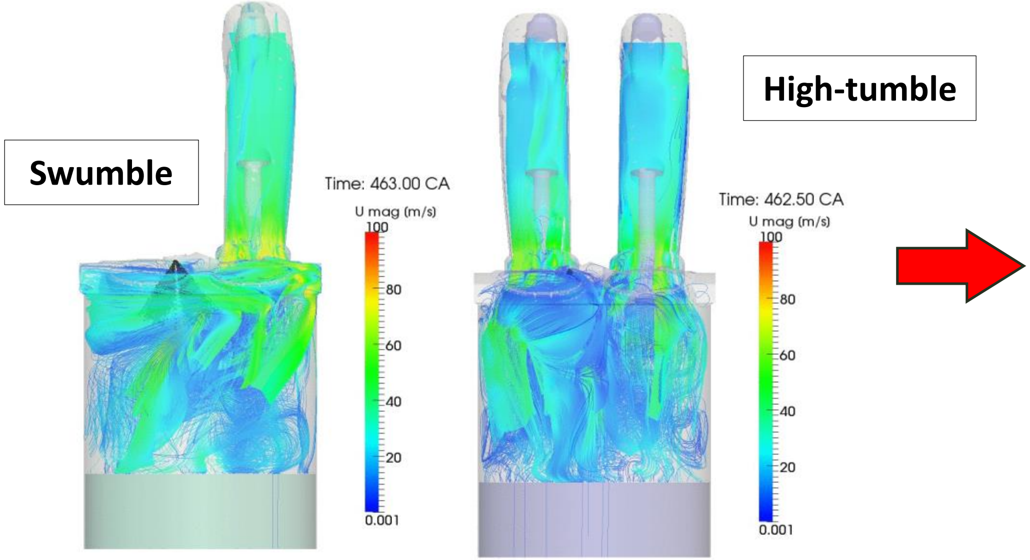

- Higher overall residual mass of wall film is observed at 700 CA for the Swumble configuration compared to both High and Standard tumble cases

# SI engines: GDI full-cycle simulations

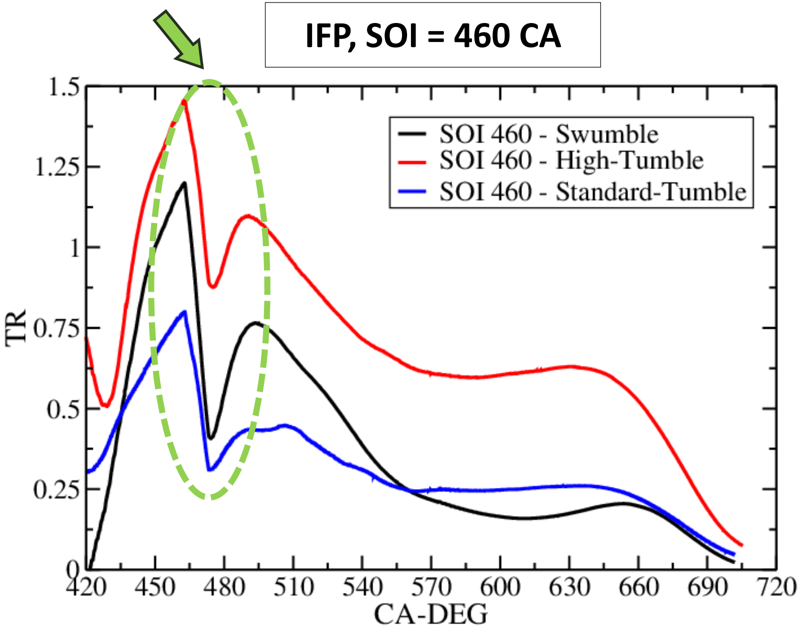


## Numerical validation. Case study: IFP optical engine

- **Air-fuel mixing:** effects of in-cylinder flow motion and turbulence on the liquid spray and vice versa




IFP, SOI = 460 CA




- For each condition, the liquid jet momentum destroys the in-cylinder tumble motion between SOI and EOI

# SI engines: GDI full-cycle simulations



## Numerical validation. Case study: IFP optical engine

**SOI = 540 CA**

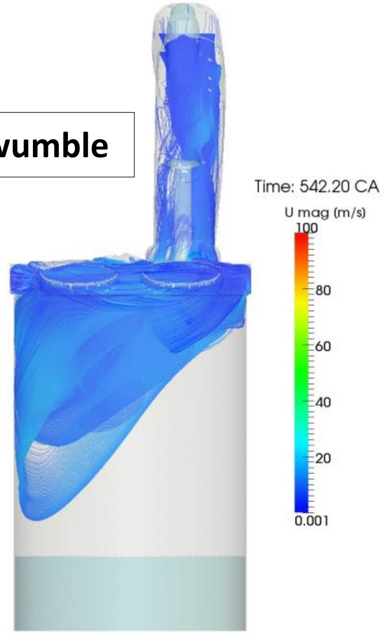
- **Air-fuel mixing:** effects of in-cylinder flow motion and turbulence on the liquid spray and vice versa

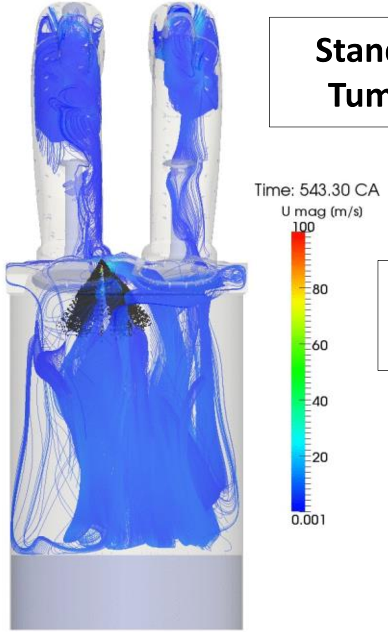
# SI engines: GDI full-cycle simulations



## Numerical validation. Case study: IFP optical engine

- **Air-fuel mixing:** effects of in-cylinder flow motion and turbulence on the liquid spray and vice versa



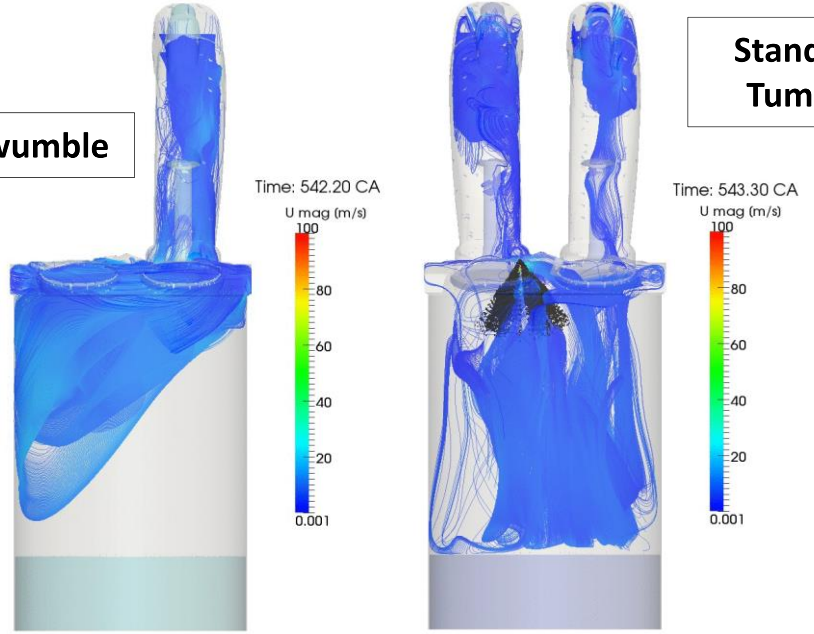
# SI engines: GDI full-cycle simulations

## Numerical validation. Case study: IFP optical engine

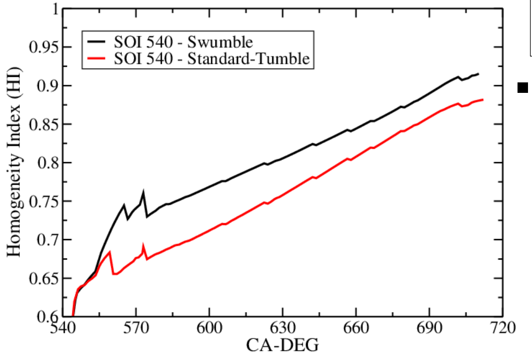
- **Air-fuel mixing:** effects of in-cylinder flow motion and turbulence on the liquid spray and vice versa

**Swumble**

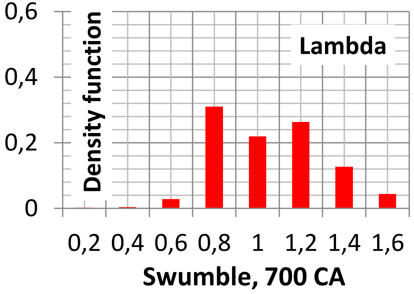
**Standard Tumble**

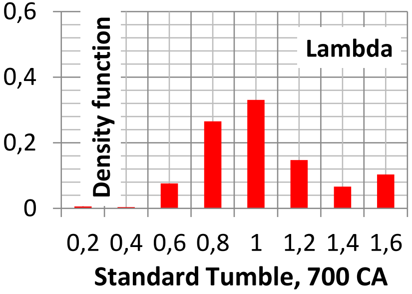



**IFP, SOI = 540 CA**




- Consistently higher promoted mixture homogeneity by the Swumble configuration



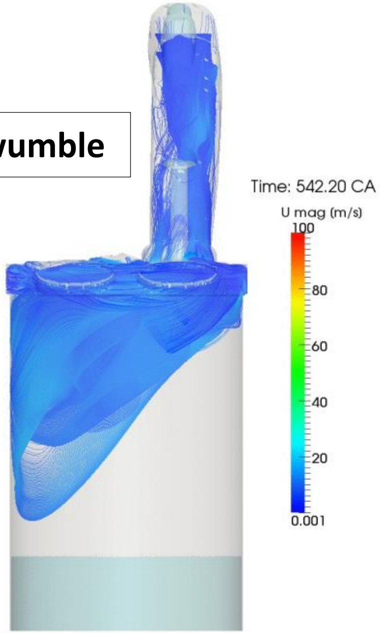

- Similar in-cylinder Lambda density distribution

# SI engines: GDI full-cycle simulations

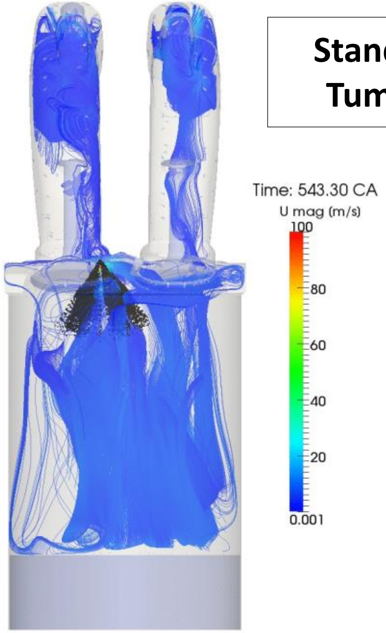
## Numerical validation. Case study: IFP optical engine

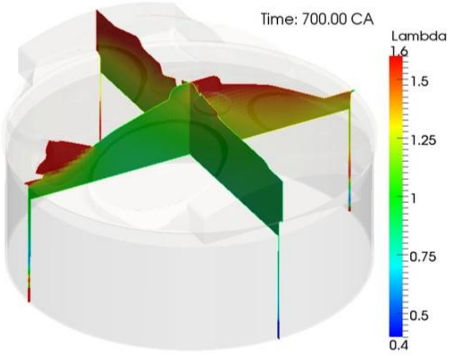
➢ **Air-fuel mixing:** effects of in-cylinder flow motion and turbulence on the liquid spray and vice versa

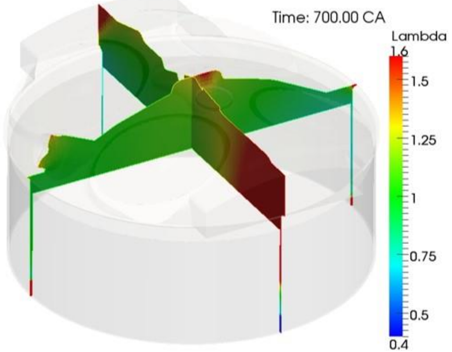
**Swumble**




**Standard Tumble**




**IFP, SOI = 540 CA**

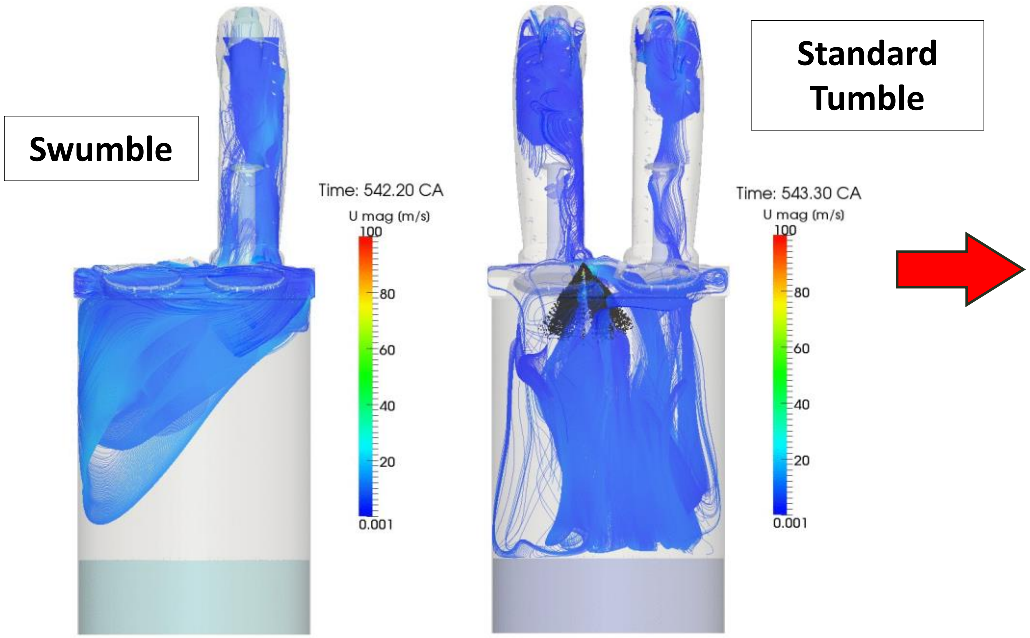
- **Swumble**: lean mixture near the spark-plug and the cylinder-head surface. Both lean and rich mixture in the crevices
- **Standard-Tumble**: mixture closer to stoich. conditions in the chamber and near the spark-plug. Very lean zone on the right intake-side

# SI engines: GDI full-cycle simulations

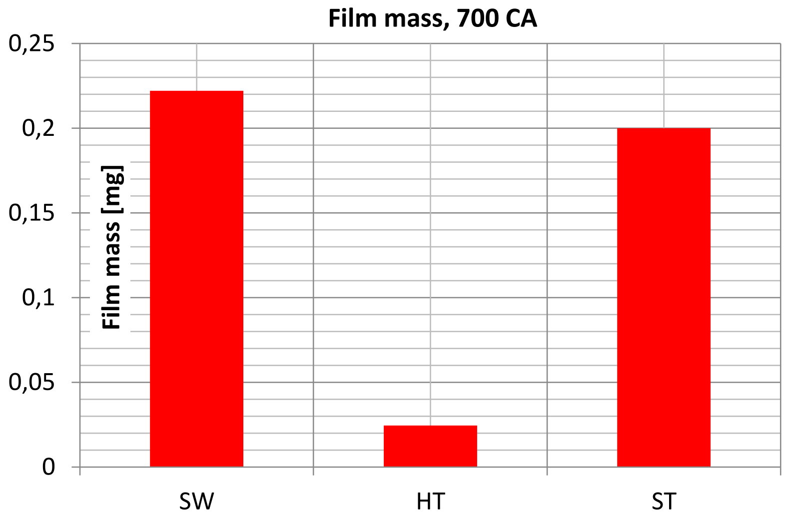


## Numerical validation. Case study: IFP optical engine

- **Air-fuel mixing:** effects of in-cylinder flow motion and turbulence on the liquid spray and vice versa




**IFP, SOI = 540 CA**

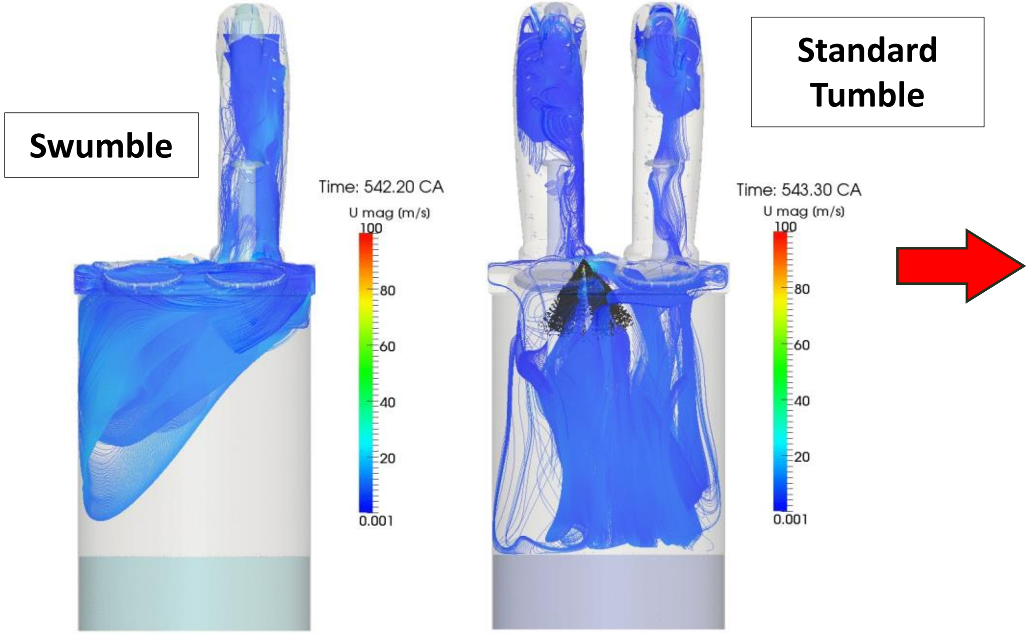



- Higher overall residual mass of wall film is observed at 700 CA for the Swumble configuration compared to both High and Standard tumble cases

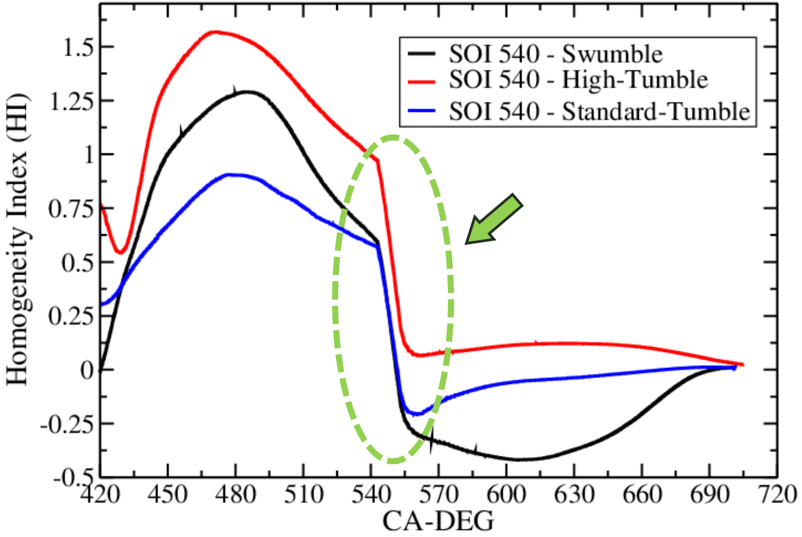
# SI engines: GDI full-cycle simulations

## Numerical validation. Case study: IFP optical engine

- **Air-fuel mixing:** effects of in-cylinder flow motion and turbulence on the liquid spray and vice versa




**IFP, SOI = 540 CA**




- For each condition, the liquid jet momentum destroys the in-cylinder tumble motion between SOI and EOI

# Conclusions

## CFD modeling of GDI injectors/engines with OpenFOAM/LibICE

- Comprehensive methodology capable to predict the most challenging physical phenomena related to modern GDI injectors and engines. Extensive support both for research and industrial design processes

Thanks for your attention!