4th Two-day ICE Simulations Using OpenFOAM®

Simulation of fuel/air mixture formation in optical Gasoline-Direct Injection engine

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Politecnico di Milano, 13.02.2020

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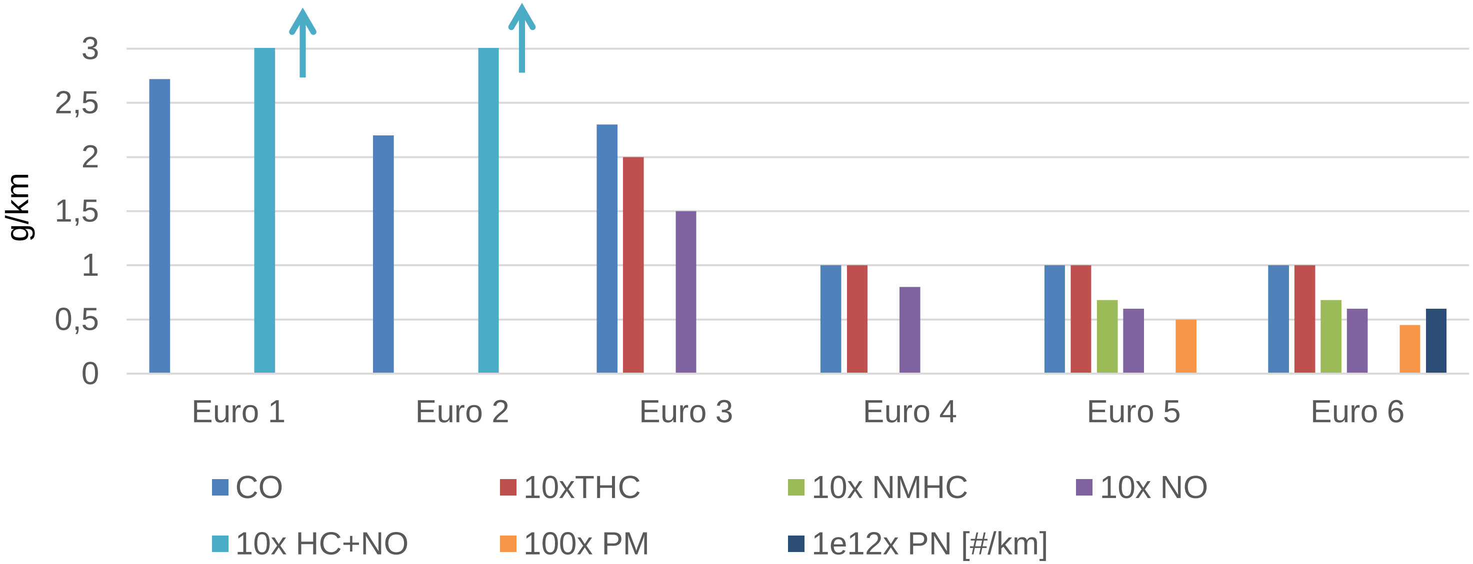
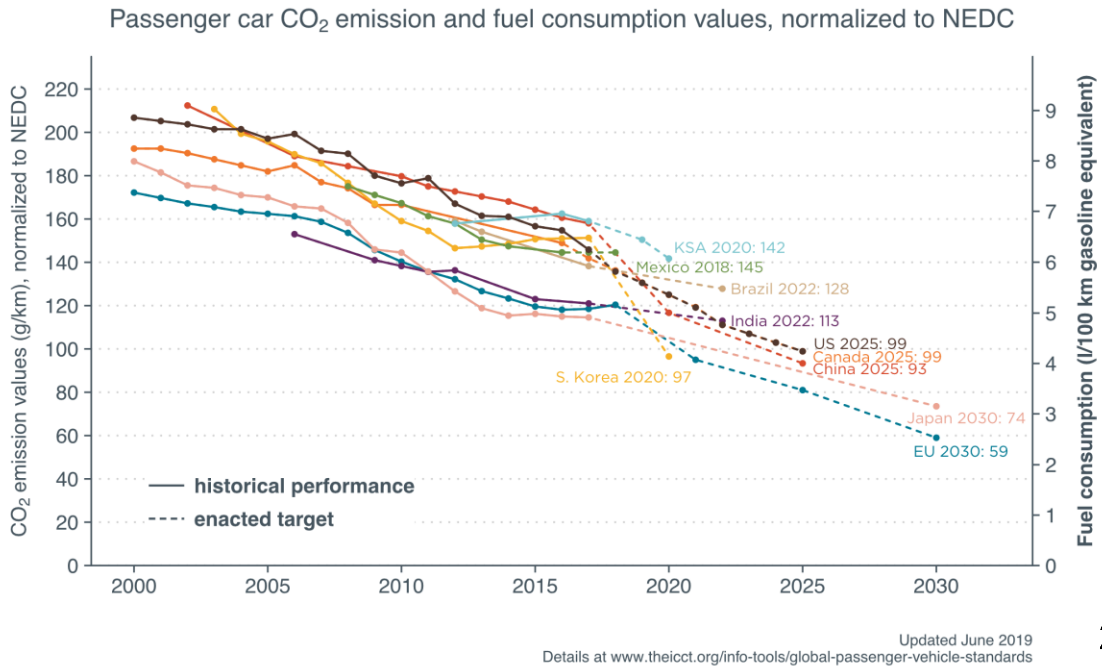
STFS

Internal combustion challenges

- Emission rules
  - Quantity reduced
  - Pollutant type more regulated
- Alternative fuels
  - Ethanol-Gasoline mixtures
  - E-Fuels
- CO_2 emission
  - Fuel consumption





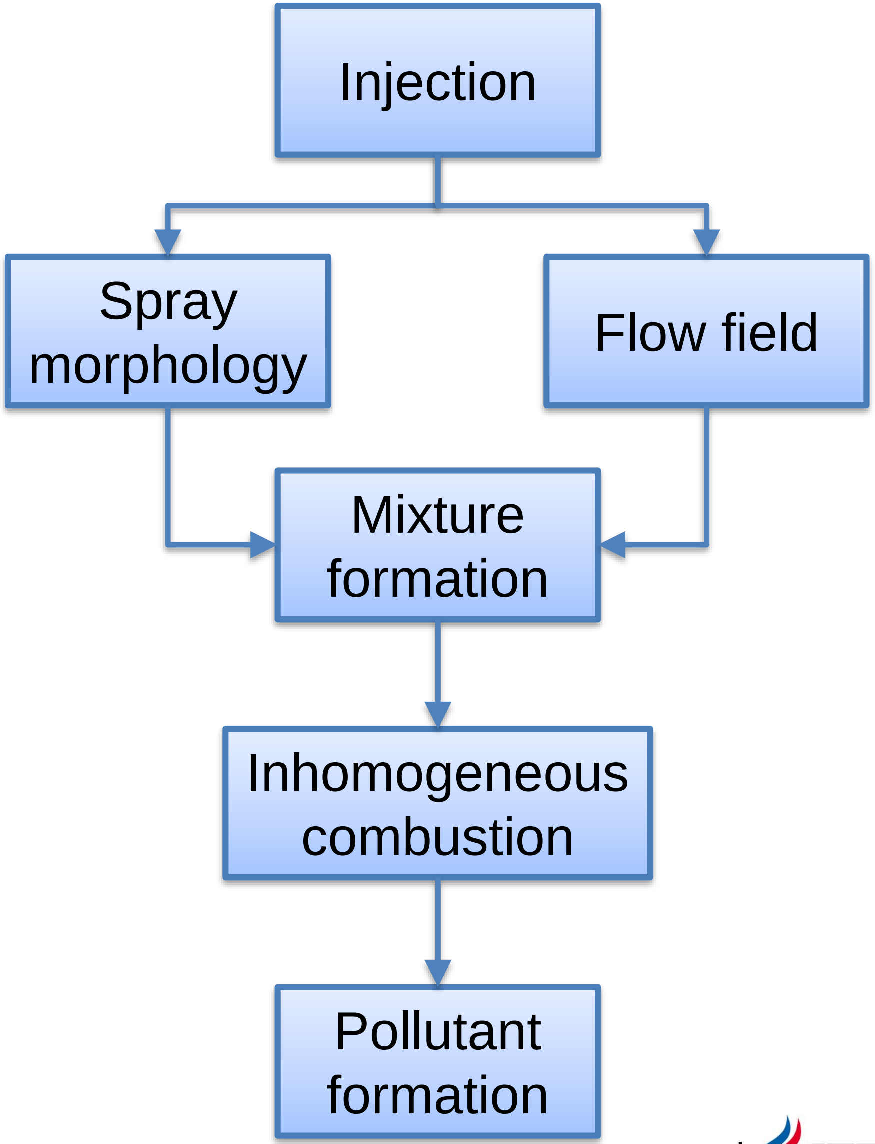
- Clean and efficiency combustion
- Understanding combustion phenomena

Internal combustion challenges

- Combustion directly affected
  - Injection process
  - Fluid flow
  - Wall interaction

- CFD as diagnostic tool to understand combustion process cause-effect chain

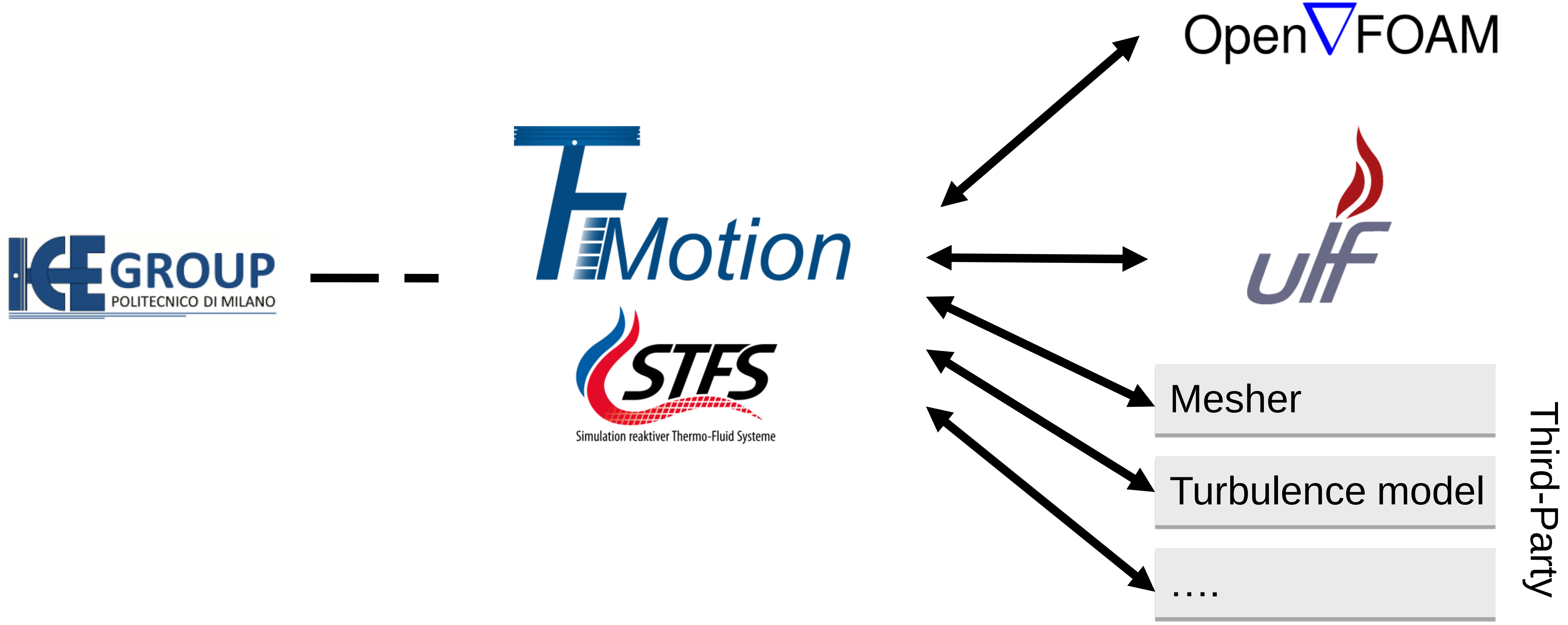
[1]



[1] Scholtissek, A. et al. (2017): Internal Combustion Engine - cause and effect chain. DOI: 10.6084/m9.figshare.5170480.v3

TFMotion

- Library developed internally at STFS
- Based on LibICE from Politecnico di Milano
- Interface to wide range of software



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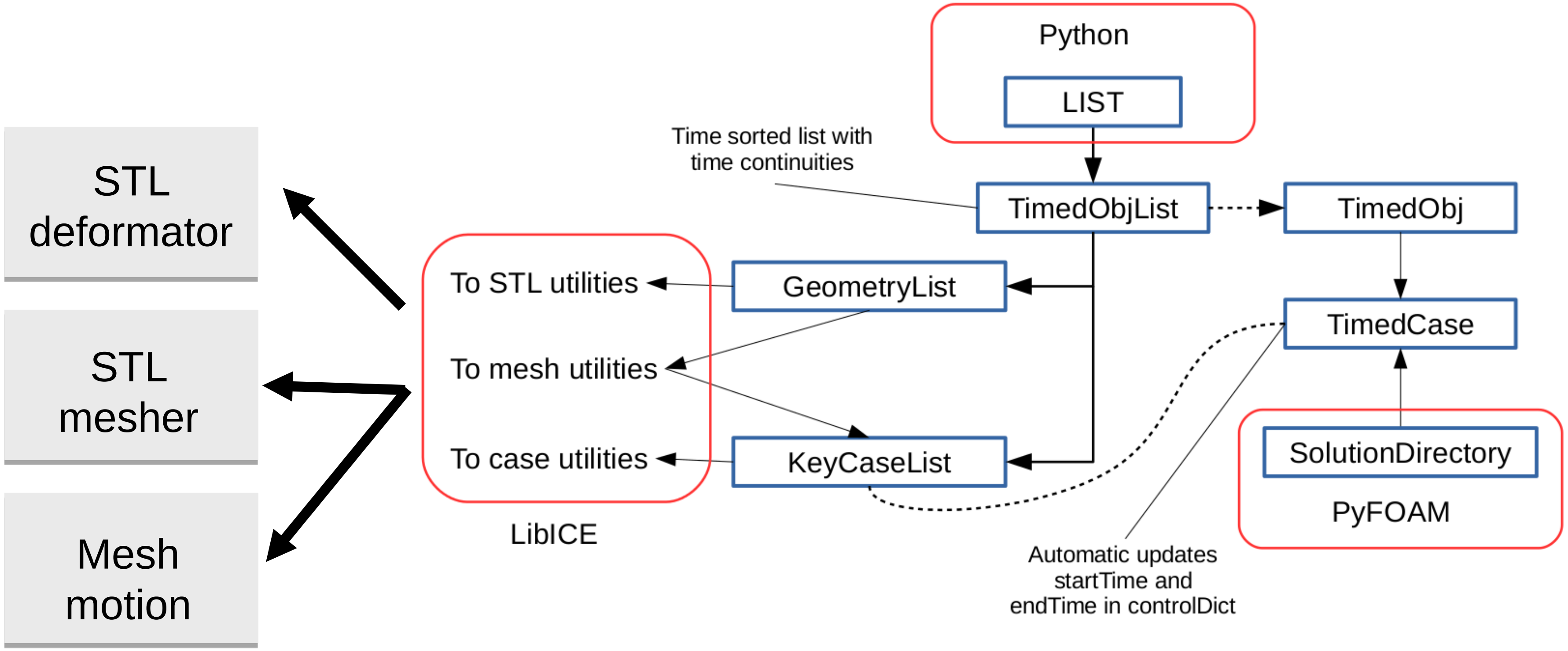
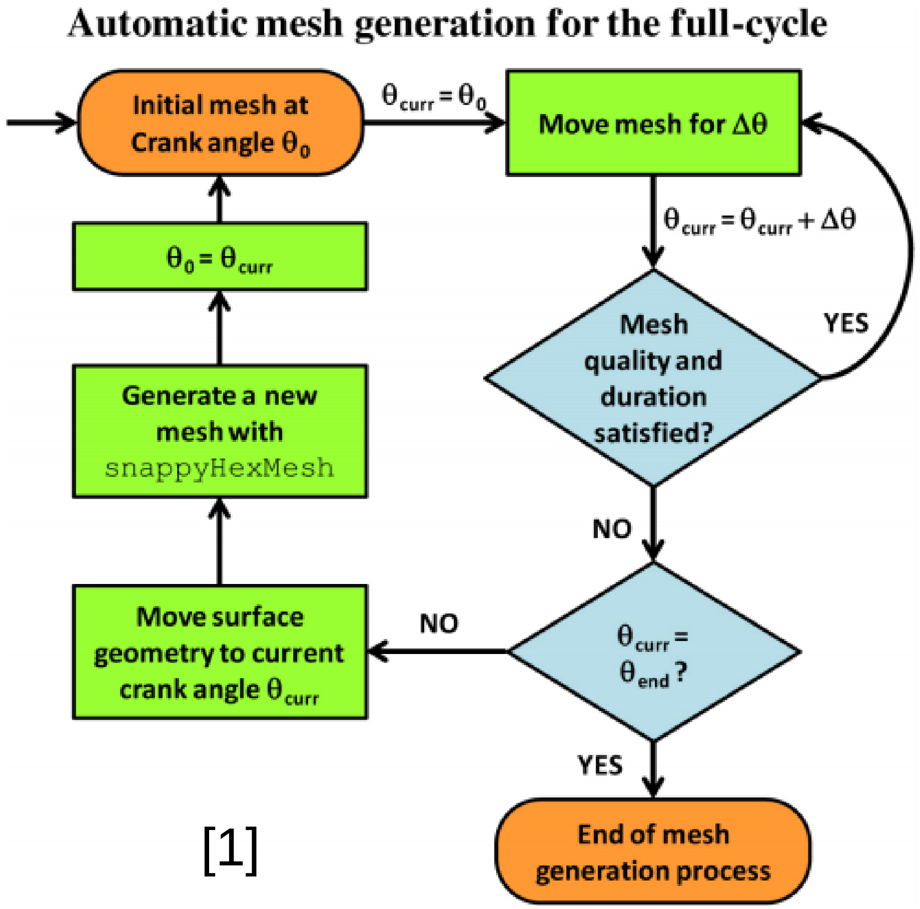
- TFMotion has been developed to increase flexibility in engine simulation
- It is composed by two sections
  - C++ code → interface to OpenFOAM
  - Python code → scripting

- Foam code and Third-Party separated
- No limitation in mesh generation
- No limitation in mesh motion methodology



- Automatic mesh generation
  - Mesh deformation
  - If quality is acceptable
    → continue deformation
  - Otherwise:
    - Modify geometry
    - Regenerate mesh

- Mesh quality insured
- Flexibility in quality criteria
- Mesher decoupled from solver and mesh motion

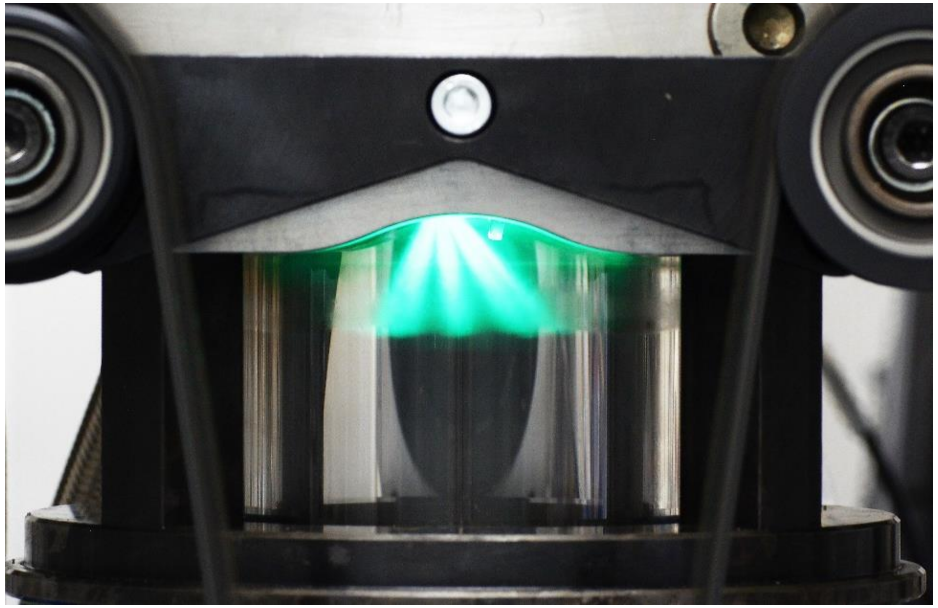


[1]

[1] Lucchini, Tommaso, et al. Automatic mesh generation for CFD simulations of direct-injection engines. No. 2015-01-0376. SAE Technical Paper, 2015.

Darmstadt optical engine

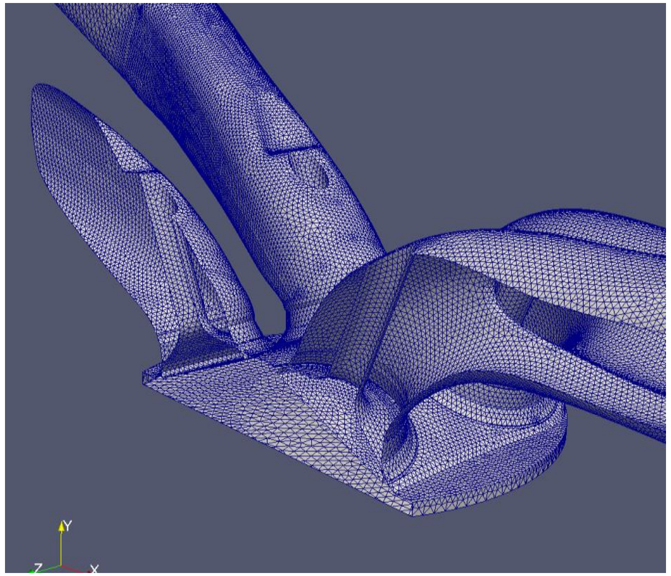
- Darmstadt optical engine
- Full optical access
- Gasoline direct injection
  - Spray guided
  - ECN Spray G
- Pent-roof 4 valve
- Spray guided
- Fired and <u>motored</u> operating condition



RSM Reaktive Strömungen + Messtechnik

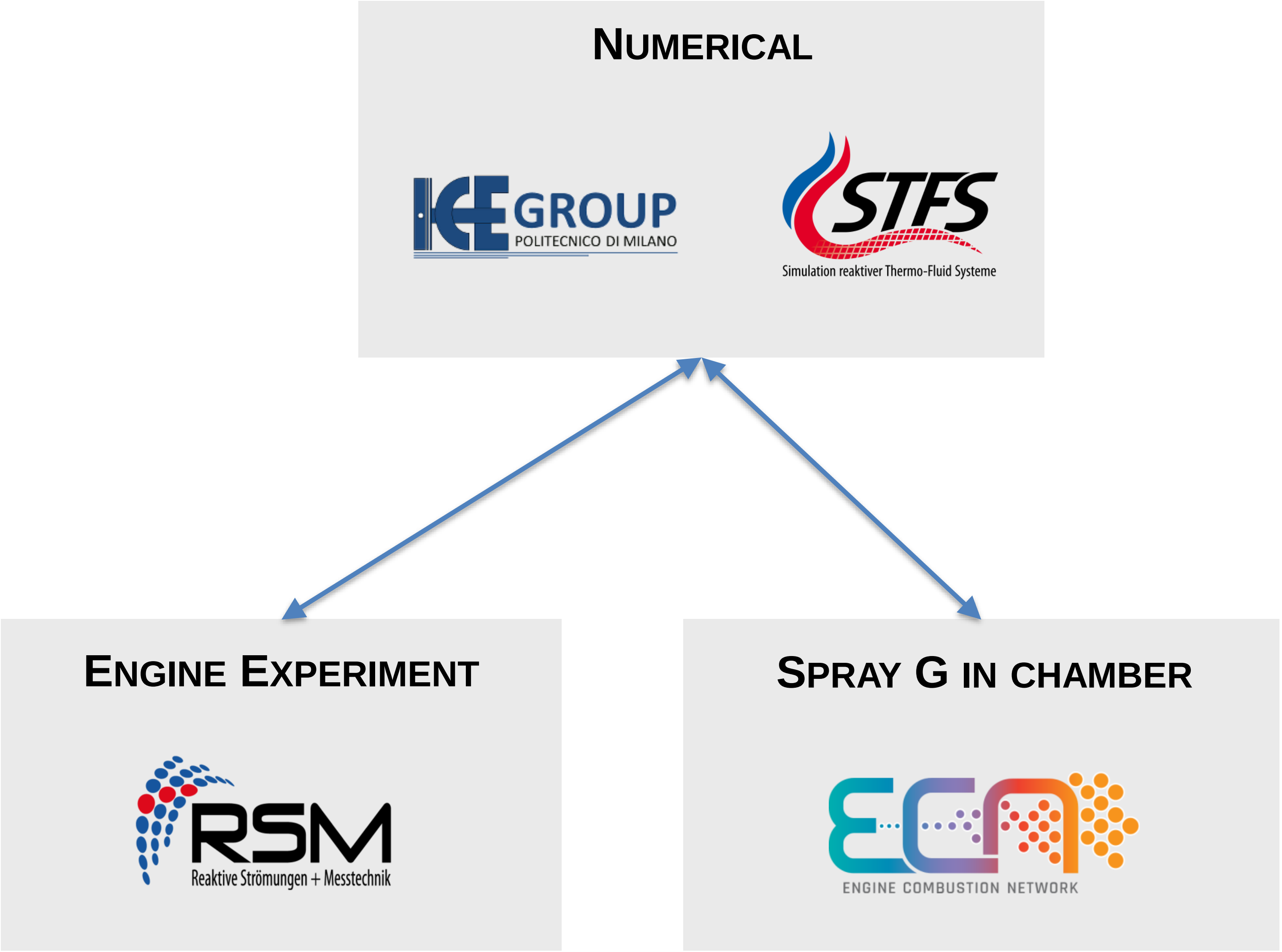
Advantages

- Different operating point available
  - Engine load
  - Engine speed
- Large amount of data available
- Full cylinder view at each crank angle



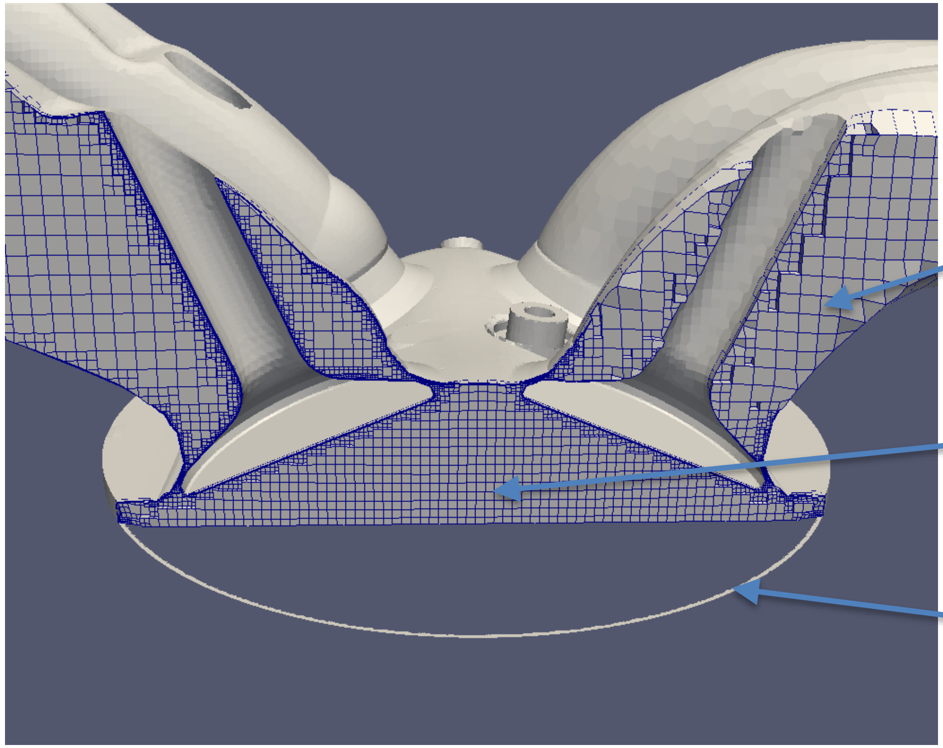
STFS Simulation reaktiver Thermo-Fluid Systeme

- Simulation methodology
  - Mesh generation and motion
  - Spray model
  - Wall film
- Motored condition
- Sprayed condition
- Conclusion and outlook



- Mesh generated with snappyHexMesh v1812

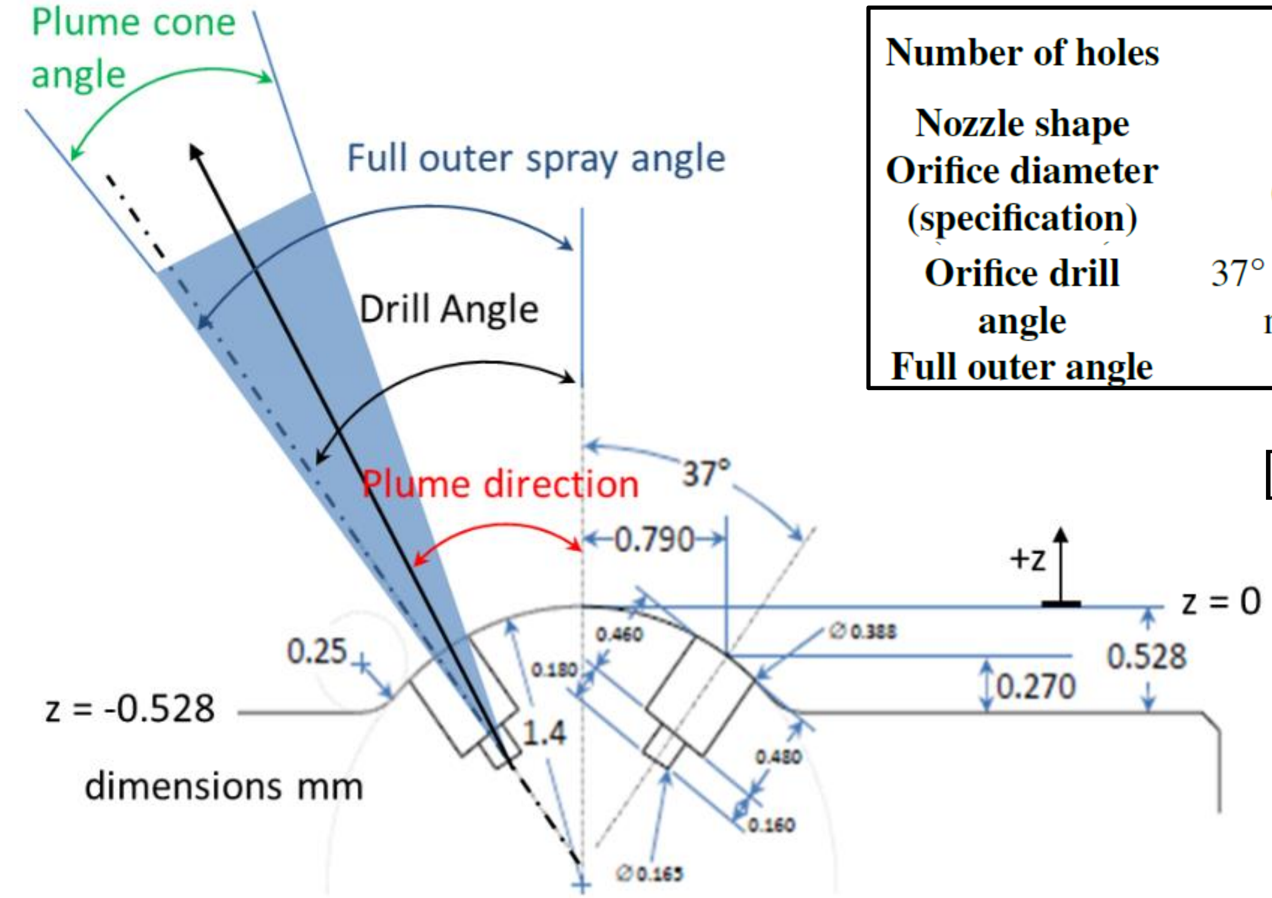
- 1.28 Mio cell
- 1 mm cell size in cylinder
  - 0.5 mm at injection
- Min. valve lift 0.5 mm
- Intake valve refined to capture flow detachment
- Crevice model → mass/momentum exchange



ADVANTAGES

- Hex-dominated mesh
- Refinement in region of interest
- Crevice models

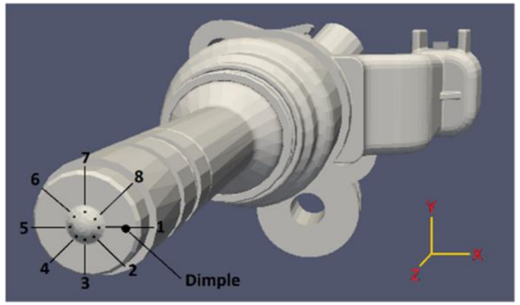
- Engine Combustion Network (ECN) both for experimental and numerical investigations
- Eight-hole GDI injector manufactured by Delphi
- Spray G3 early injection operating point



Number of holes	8 (equally spaced)
Nozzle shape	Step hole
Orifice diameter (specification)	0.165 mm
Orifice drill angle	37° relative to the nozzle axis
Full outer angle	80°

[1]

Spray G3	
Fuel	Iso-octane
Fuel temperature	363.15 K
Ambient temperature	333 K
Injection pressure	200 bar
Ambient density	1.01 kg/m^3
Injected mass	10 mg
Injection duration	780 µs



[1] https://ecn.sandia.gov/gasoline-spray-combustion/computational-method/mesh-and-geometry/

Spray in vessel: the numerical model

- **Breakup**: **comprehensive Kelvin-Helmholtz and Rayleigh-Taylor (KHRT)** model optimized both for GDI sprays

Injection	Blob injection Cd = 0.73
Primary atomization	Pilch-Erdman
Secondary breakup (KH)	B0: 0.61 B1: 23.0
Secondary breakup (RT)	CRT: 0.35

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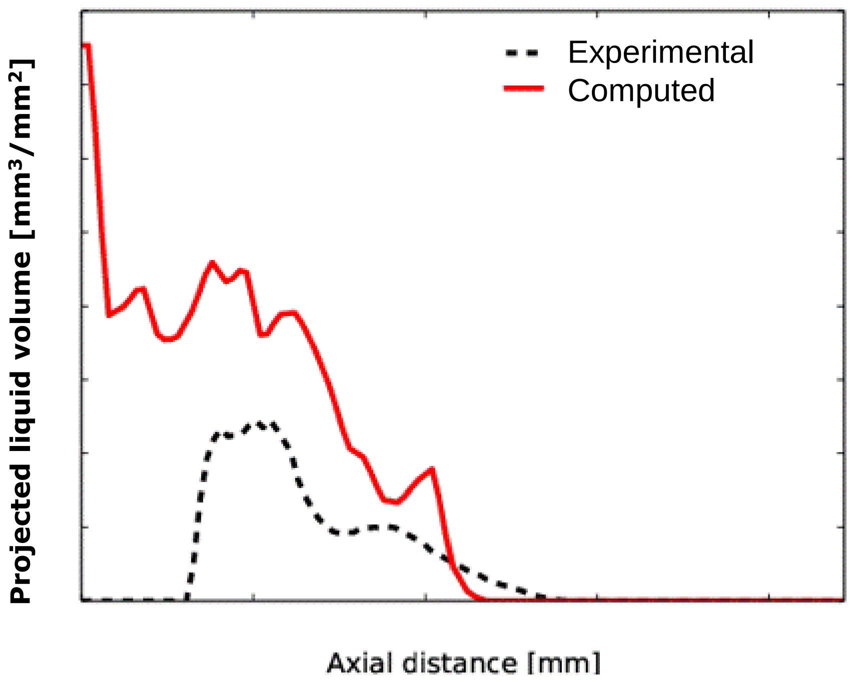
- **Assessed quantities:**
  - Axial vapor penetration
  - Axial liquid penetration (double threshold based on projected liquid volume)
  - Centerline gas velocity
  - Spray morphology and in-plume mass distribution at different times

Spray in vessel: low-evaporating G3 condition results

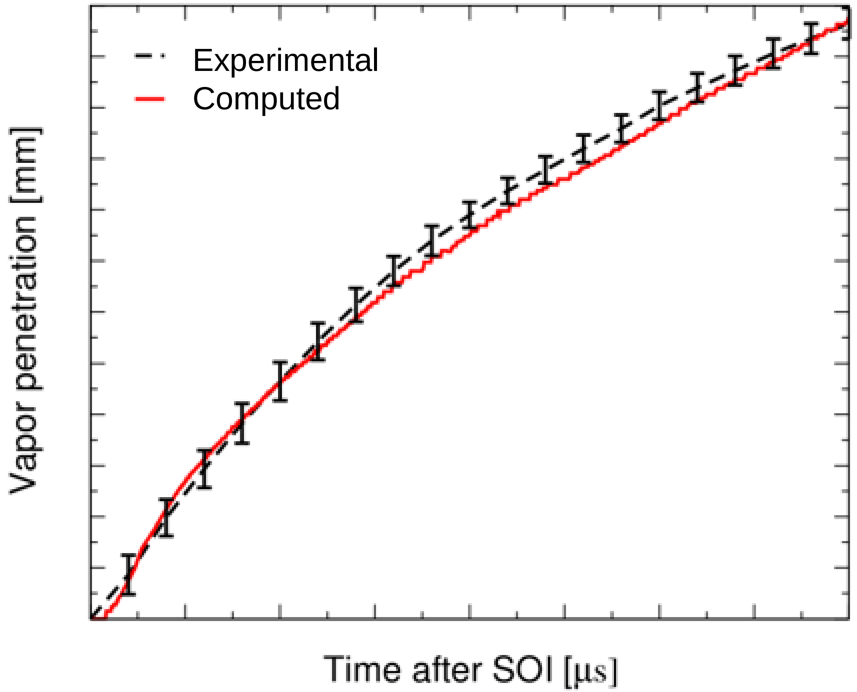
- Several operating point available on ECN
- G3 close to ambient condition, low-evaporating

Name	T_{fuel} [K]	T_a [K]	ρ_a [kg/m³]	Ambient pressure [kPa]
G3	363	333	1.12	100

Axial PLV profiles

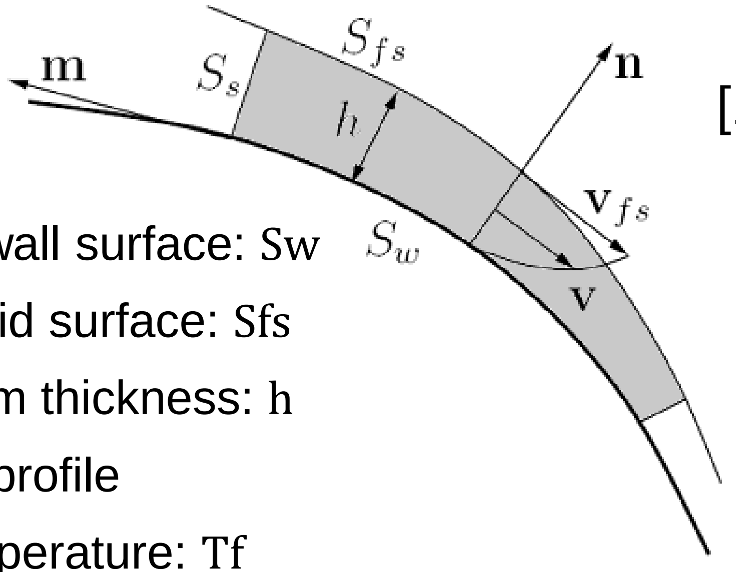


Axial vapor penetration



- Good matching between the liquid distribution inside the computed spray plumes and the experiments at different times
- Accurate reproduction of the axial vapor penetration trend

- Approach proposed by Bai and Gosman
- Simulation of the fuel film flow on an arbitrary configuration.
- Thin film approximation:



[1]

  - Curved wall surface: Sw
  - Free liquid surface: Sfs
  - Liquid film thickness: h
  - Velocity profile
  - Film temperature: Tf
- Equations are solved for film mass, momentum and energy

- Mass conservation is solved for the film thickness
- Film density depends on its temperature which affected by evaporation and heat transfer.

- Mass conservation can be an issue because of density changes.
- Film density ρ_{film} is assumed to be uniform and is enforced to fullfill the instantaneous mass conservation:

$$\mathrm{m_{injected}} = \mathrm{m_{film}} + \mathrm{m_{spray}} + \mathrm{m_{vap}}$$

$$\rho_{\mathrm{film}} = \frac{\mathrm{m_{film}}}{\mathrm{V_{film}}} = \frac{\mathrm{m_{impinged}} - \mathrm{m_{evaporated}}}{\int_s \mathrm{hds}}$$

- $\mathrm{m_{film}}$: impinged mass corresponding to the expected mass present in the wall film.

[1] Lucchini, T., et al. Development and application of a computational fluid dynamics methodology to predict fuel/air mixing and sources of soot formation in gasoline direct injection engines. *International Journal of Engine Research*, 15(5):581–596, 2014.

Agenda

- Simulation methodology
  - Mesh generation and motion
  - Spray model
  - Wall film
- Motored condition
- Sprayed condition
- Conclusion and outlook

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ENGINE EXPERIMENT

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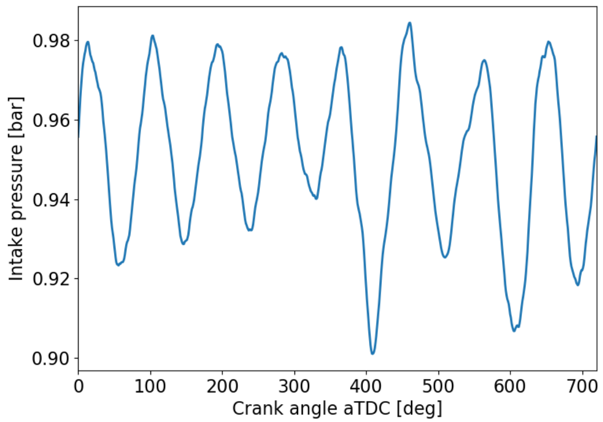
SPRAY G IN CHAMBER

ECN ENGINE COMBUSTION NETWORK

- 4 operating point investigated
  - Engine speed 800-1500 rpm
  - Intake pressure from experiment, dependent on CA
- Simulation performed with OpenFOAM 2.4.x
- URANS simulation
- k-Epsilon turbulence model
- Discretization schemes
  - Limited linear (linear upwind for momentum transport)
- Gas temperature at wall fixed at 60°
  - Huh-Chang thermal wall function [1]
- Scalable wall function



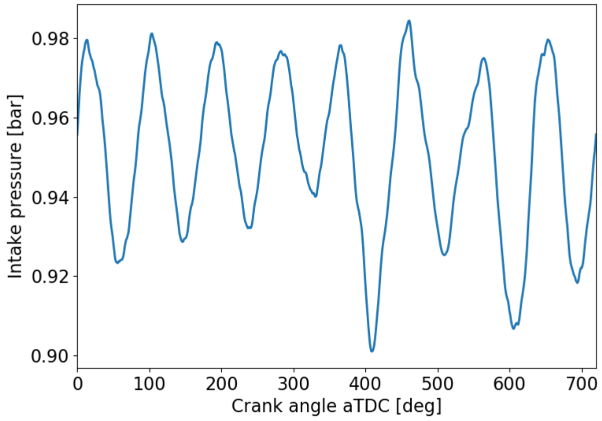
Intake pressure OP A
(curve change with OP)

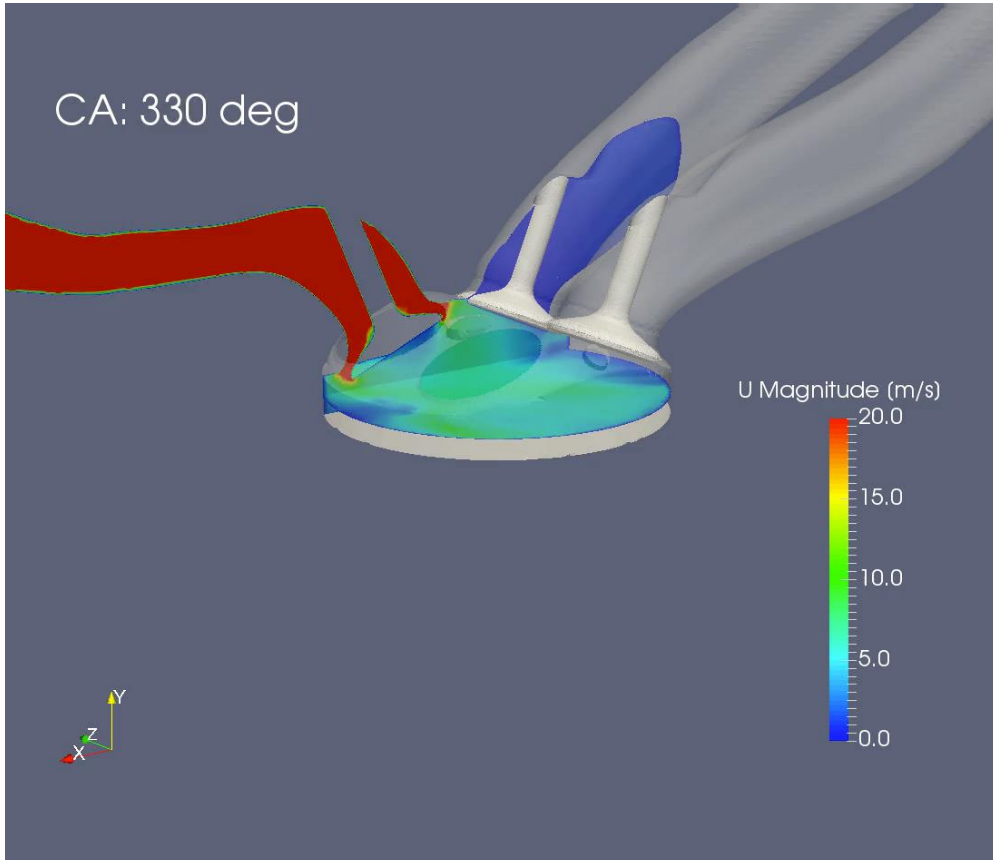
Pin	800 rpm	1500 rpm
0.95 bar	A	C
0.40 bar	B	D

[1] Huh KY, A comparison of boundary layer treatment for heat transfer in IC engines, SAE paper 900252, 1990

Motored condition

- Motored engine full cycle simulation
- Operating point A
- Interaction of flow with fixed and mobile wall





Exhaust valve omitted for simplicity

- Manifold dynamic visible
- Tumble generation
- Interaction of flow with moving wall
  → Compression
  Stronger parallel flow
  → Expansion
  Stronger perpendicular flow

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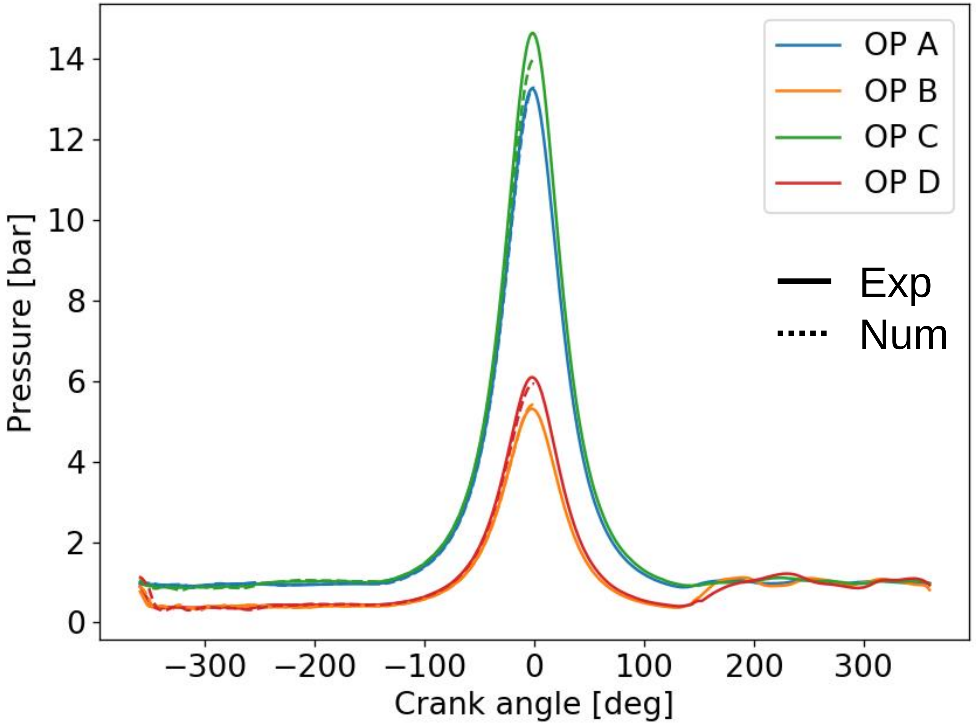
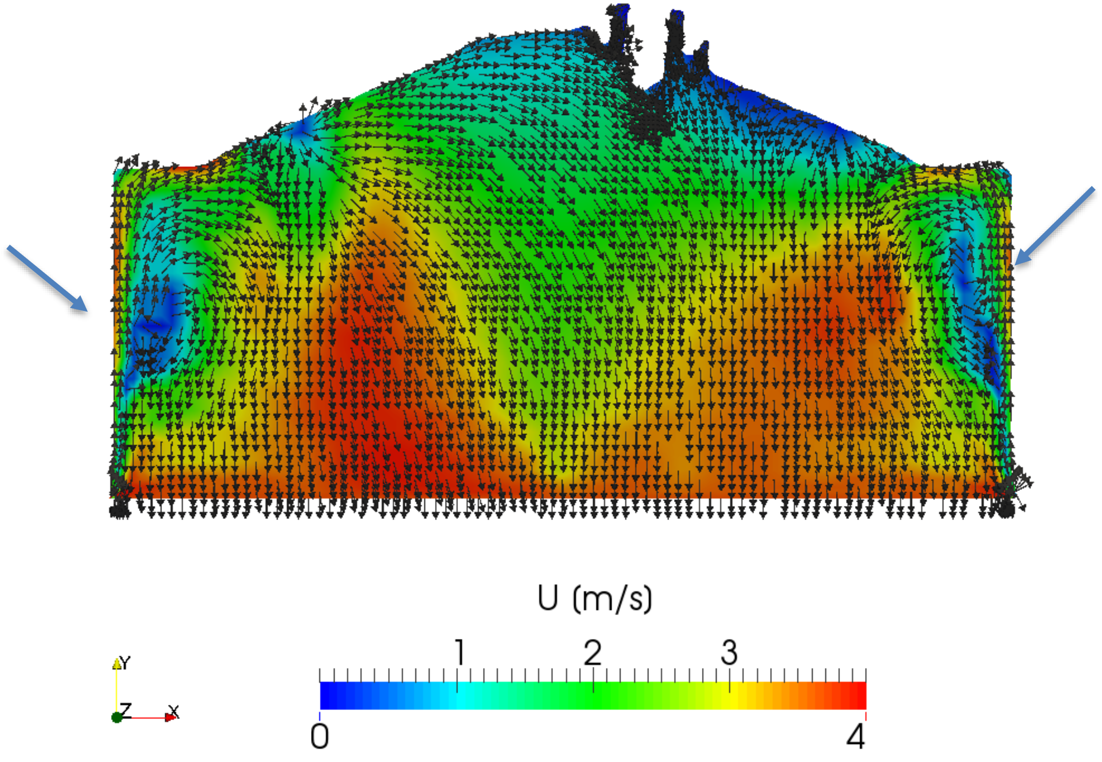
Data at TDC

OP	pressure [bar]	Mas (crevice excluded) [mg]	Mass in crevice [mg]	TKE at TDC [m^2/s^2]	Norm. TKE at TDC [-]
A	13.27	418.72	140.53	2.87	0.5457
B	5.41	164.59	57.29	2.74	0.5210
C	13.97	417.49	147.94	13.20	0.7139
D	5.93	178.62	62.80	13.70	0.7409



- Large amount of mass trapped in crevice
- TKE mainly dependent from regime
- Good match with experimental data
  - Match peak pressure
  - Match pressure during compression
- Underestimation peak pressure of OP C → Is a different heat transfer model for this operating point required?

Motored condition – effect of crevice



Recirculation region

$$\dot{m}_{cyl\rightarrow 1} = \frac{m_{0,1}}{P_{0,1}}\frac{dP_1}{dt}$$

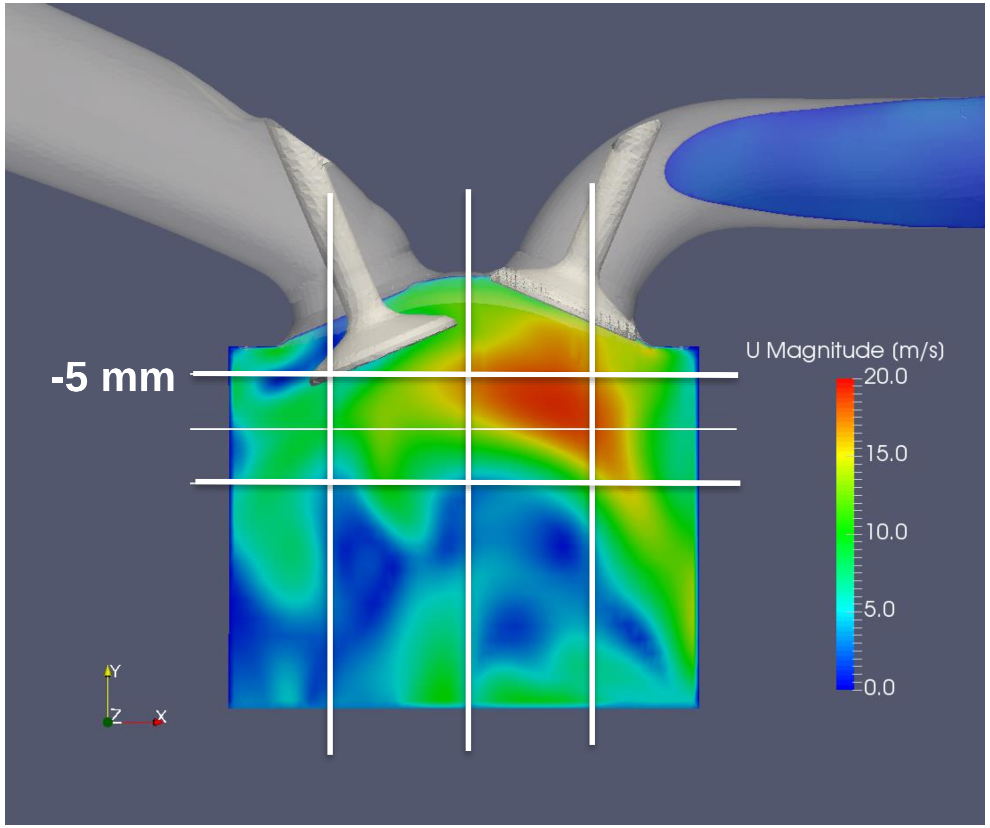
- Large amount of mass trapped in crevice
- Momentum exchange between crevice and combustion chamber
- Large impact during expansion phase

- Crevice model based on mass and momentum exchange shows effect of jet stream on expansion phase

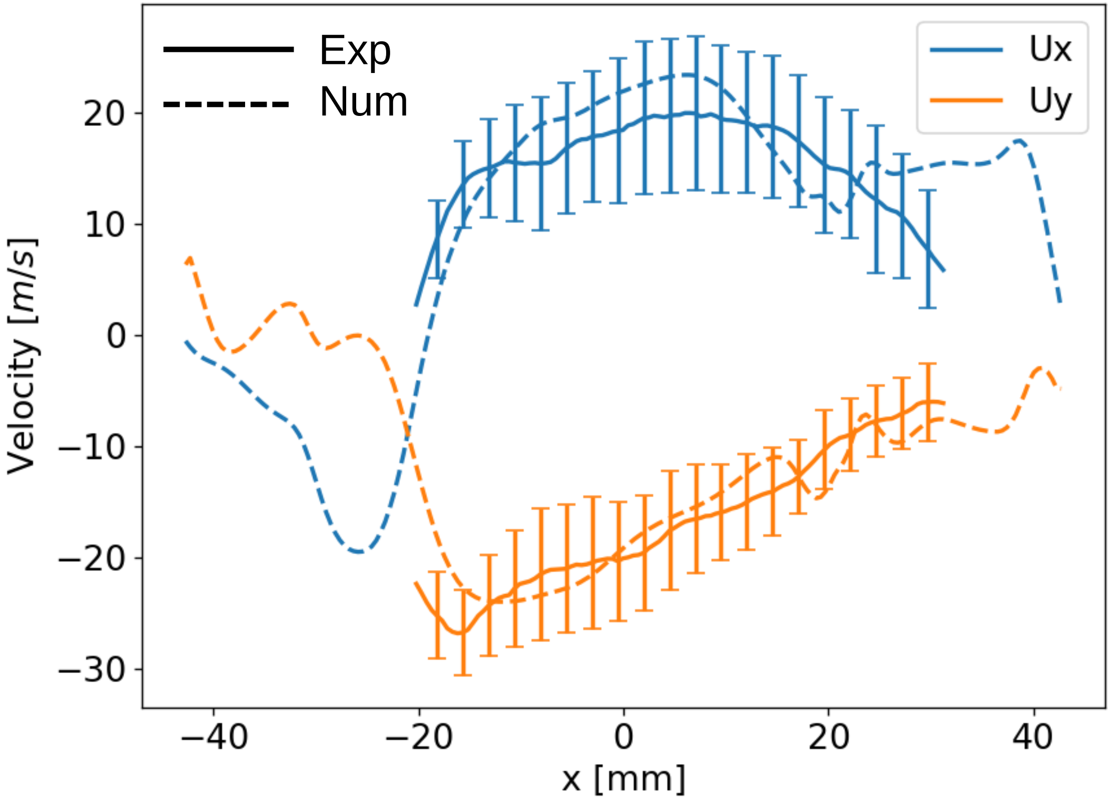
[1] Namazian, Mehdi, and John B. Heywood. "Flow in the piston-cylinder-ring crevices of a spark-ignition engine: Effect on hydrocarbon emissions, efficiency and power." SAE transactions (1982): 261-288.

Motored results – Velocity fields operating point A

- Quantitative comparison of velocity fields
- Experimental data from PIV measurements
- Tumble plane
- Operating point A – Full load, 800 rpm



Crank angle = 270° bTDC



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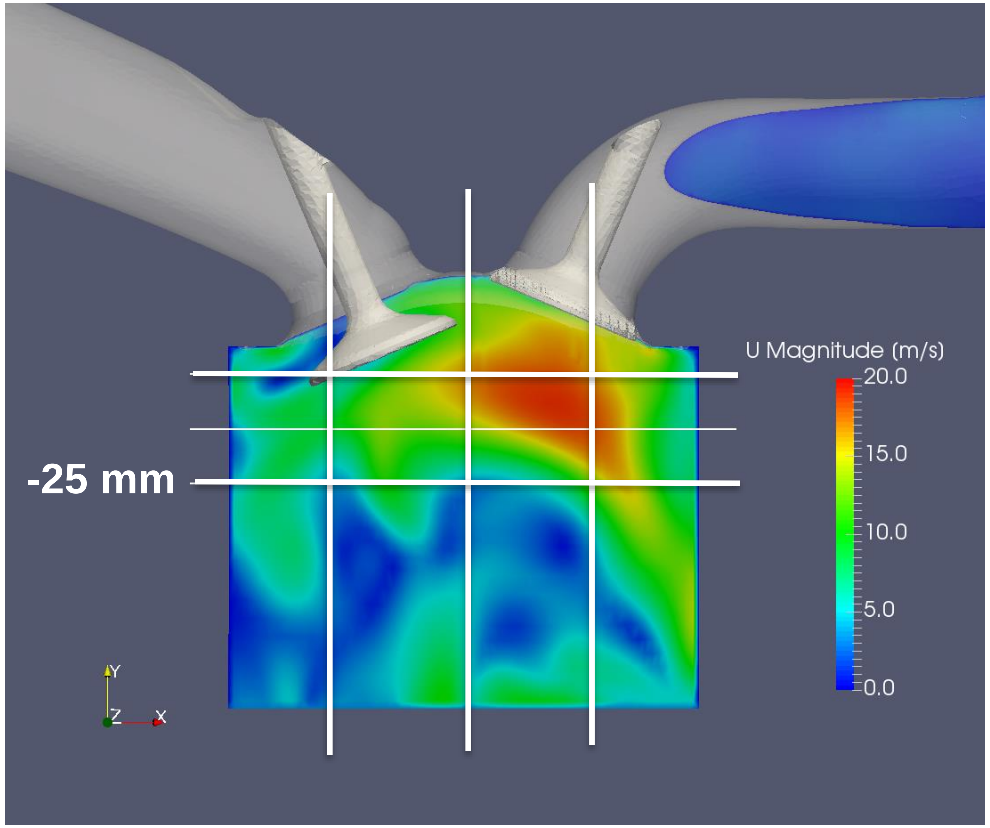

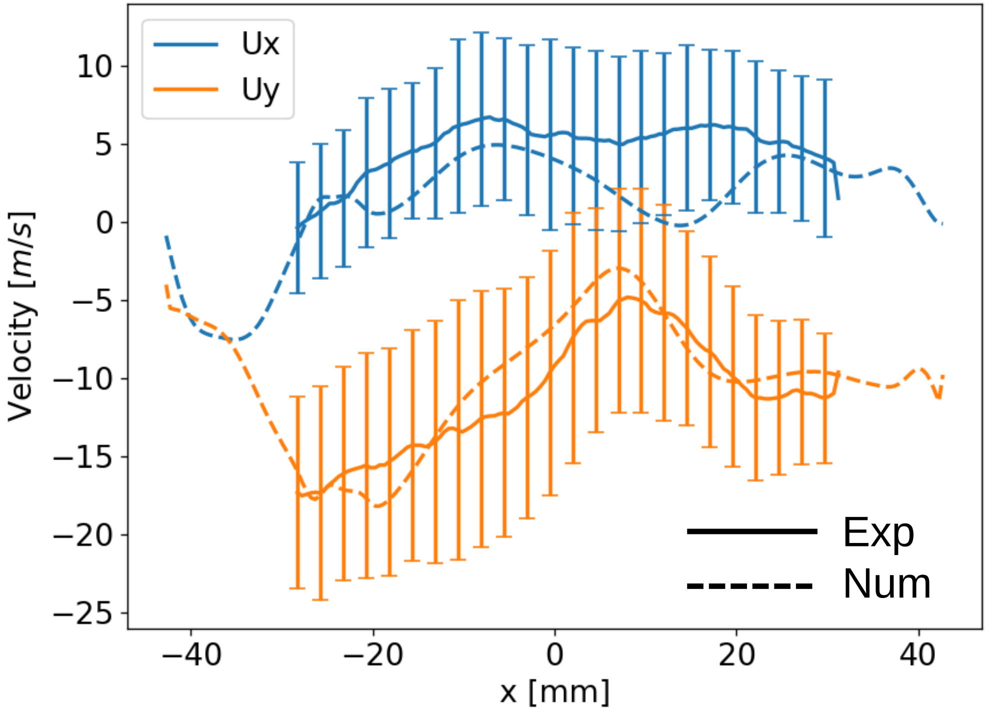

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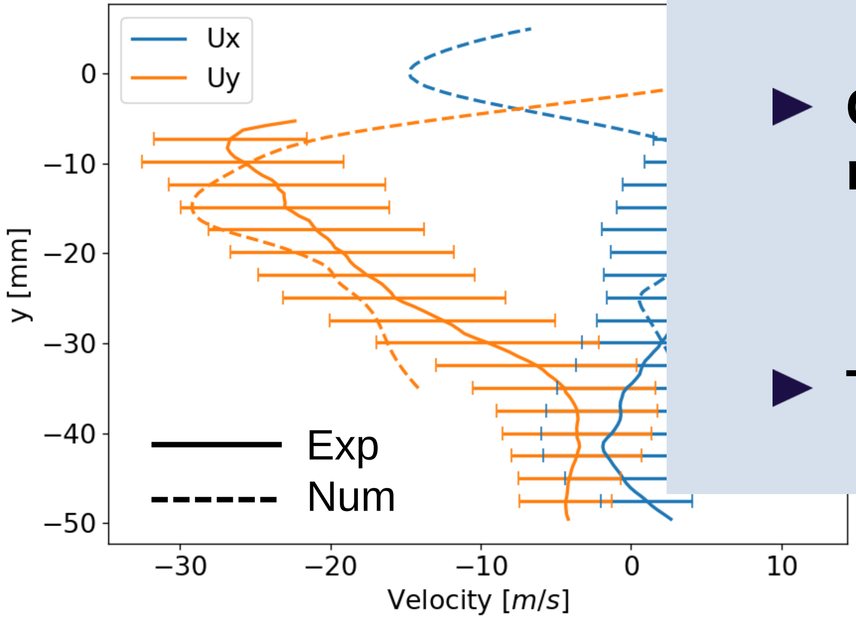

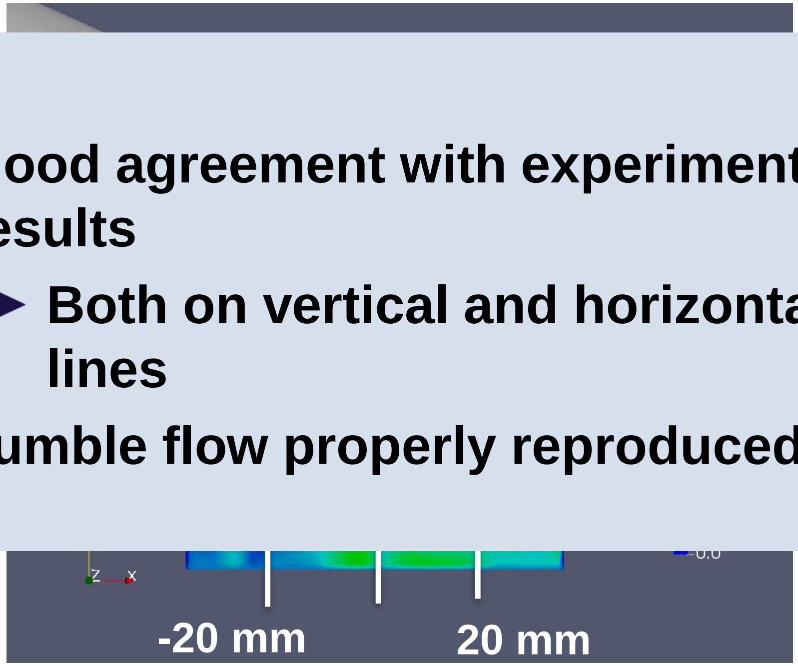

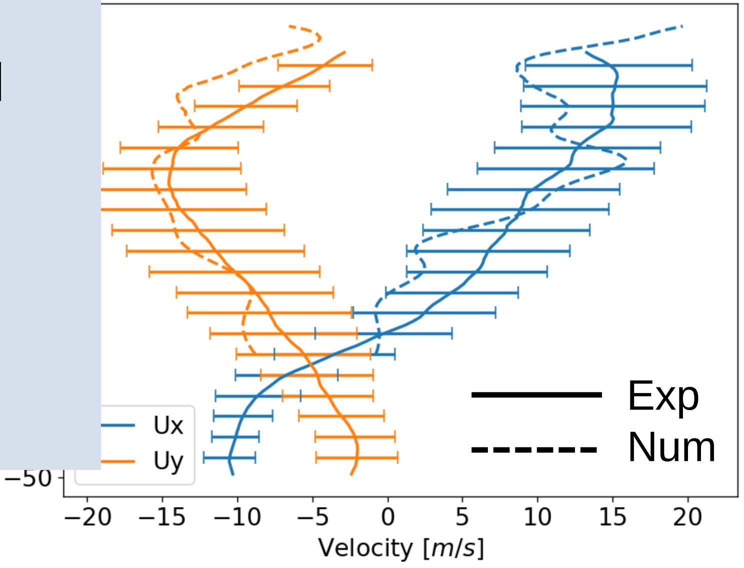

- **Good agreement with experimental results**
  - **Both on vertical and horizontal lines**
- **Tumble flow properly reproduced**

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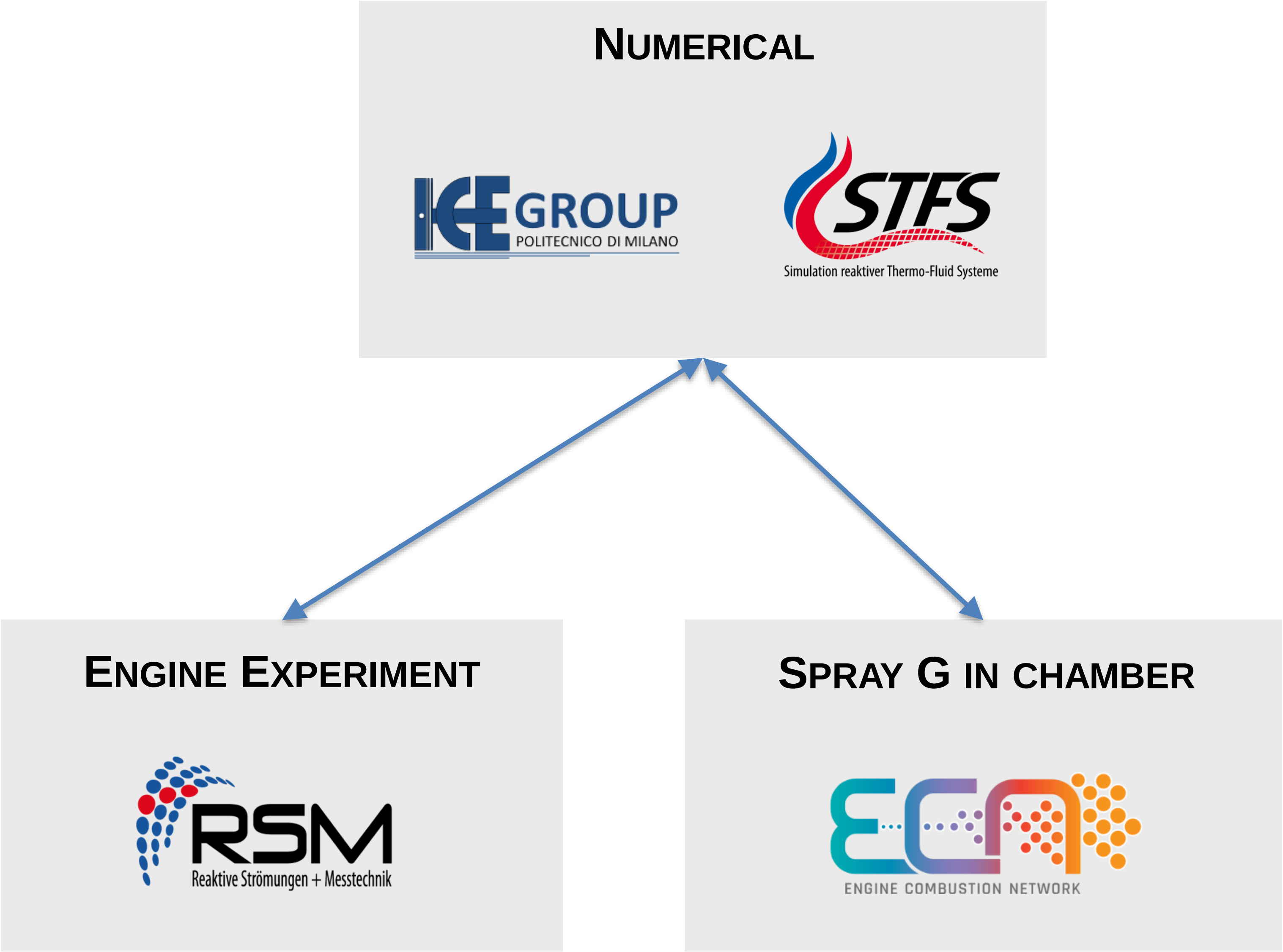

Spray condition

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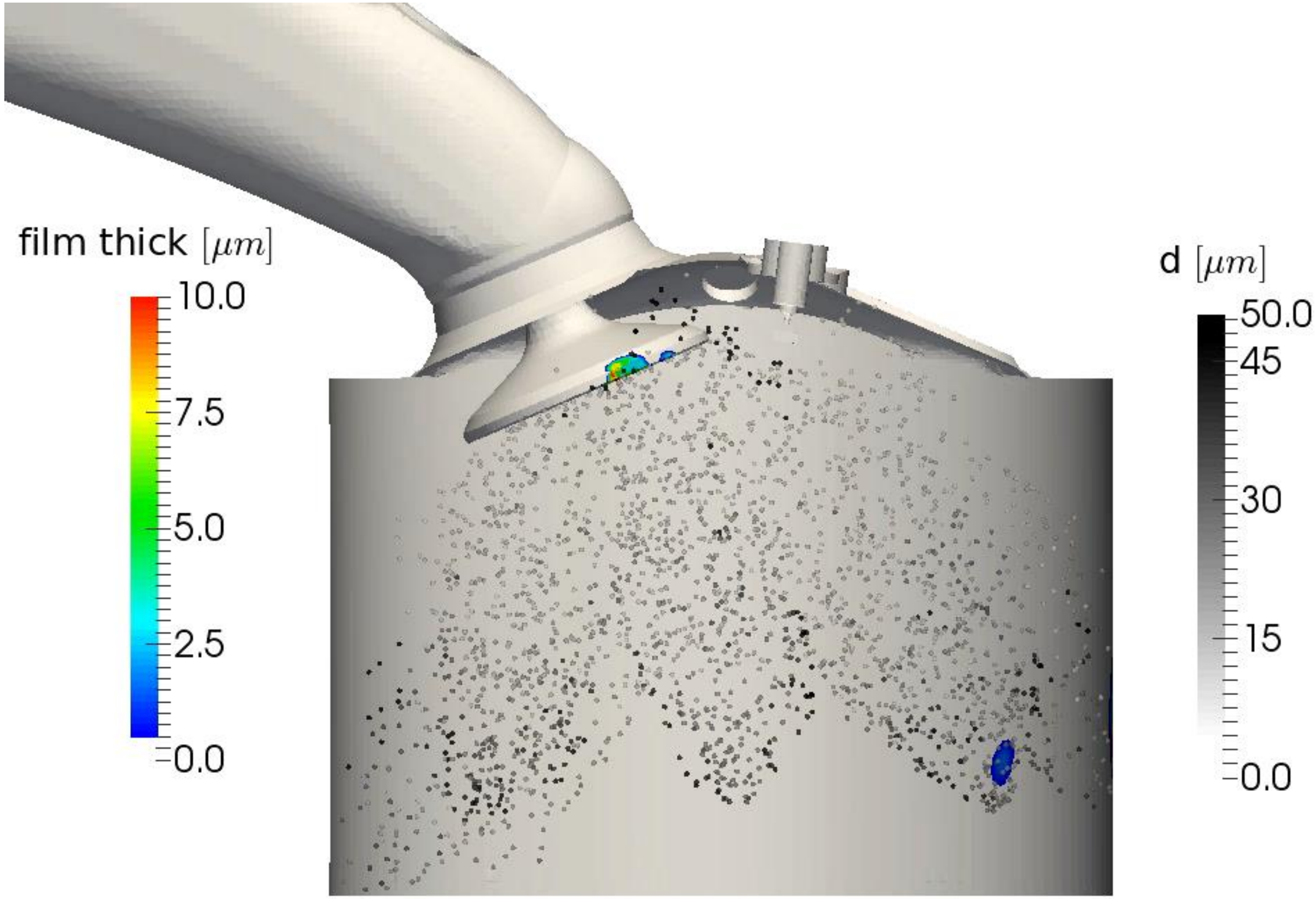
- Gas temperature at wall fixed at 60°
  - Huh-Chang thermal wall function [1]
- KHRT breakup
- Wall film model w/ Bai-Gosman

- Spray G injector
- Iso-octane
- Operating point G3
  - ESOI 270° bTDC

[1] Huh KY, A comparison of boundary layer treatment for heat transfer in IC engines, SAE paper 900252, 1990

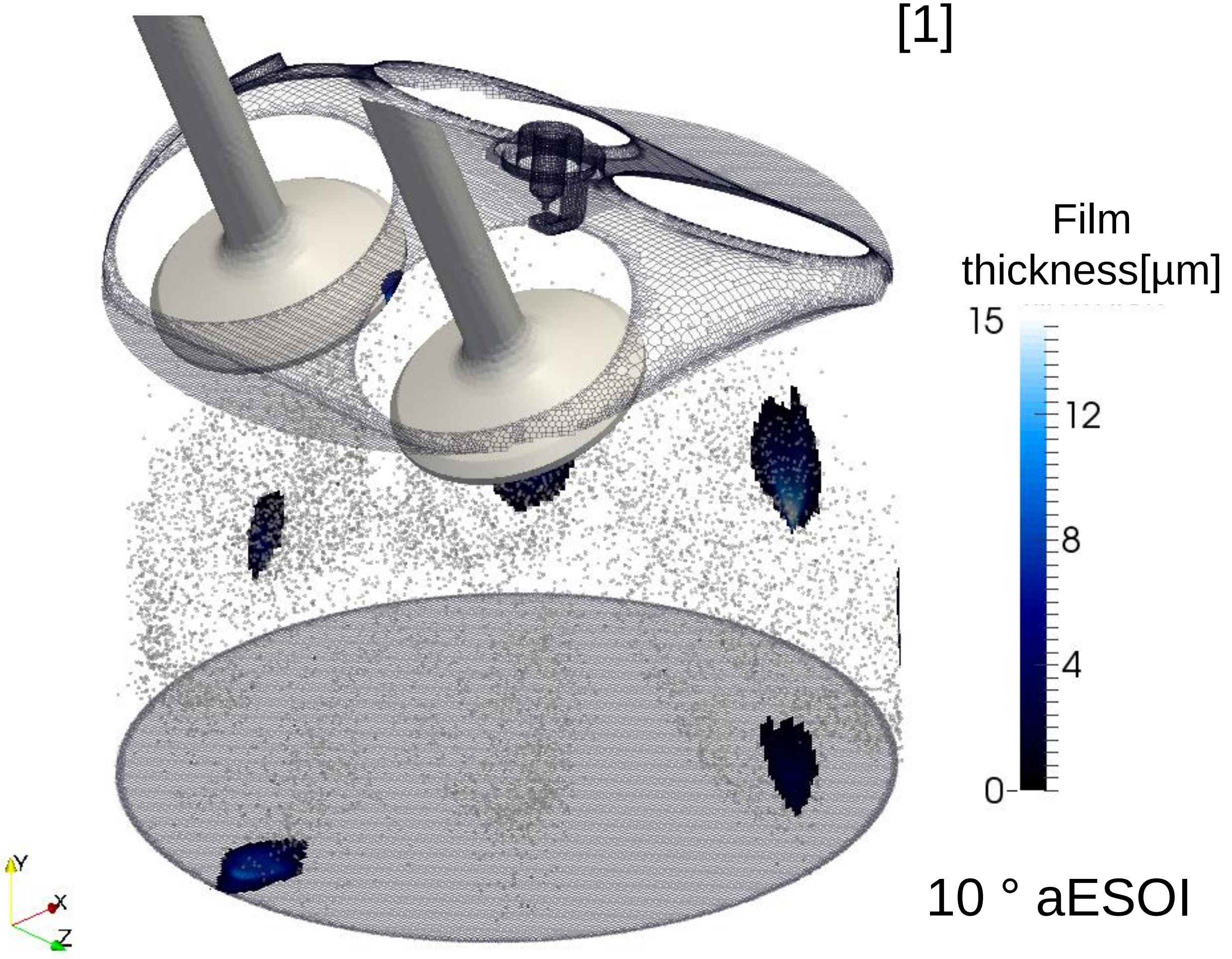
Spray condition – operating point A

- Qualitative analysis of results



- Underflow plume:
  - Higher penetration
  - Wall film produced on piston
- Overflow plume:
  - Penetration similar to other plume
  - Wall film produced on liner
- Strong interaction with valve
- Wall film on liner at end of injection

- Distribution of wall film

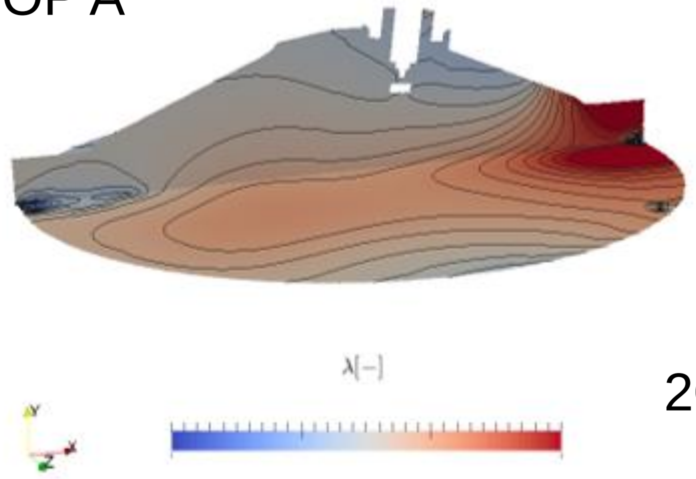


- Underflow plume:
  - Higher penetration
  - No wall film produced
- Overflow plume:
  - Penetration similar to other plume
  - Wall film produced
- Strong interaction with valve
- Wall film on liner at end of injection

[1] A. Pati, D. Paredi, T. Lucchini, C. Hasse: CFD Modeling of Gas-Fuel Interaction and Mixture Formation in a Gasoline Direct-Injection Engine Coupled With the ECN Spray G Injector, accepted for publication on *SAE paper* 2020-01-0327

Fuel / air distribution

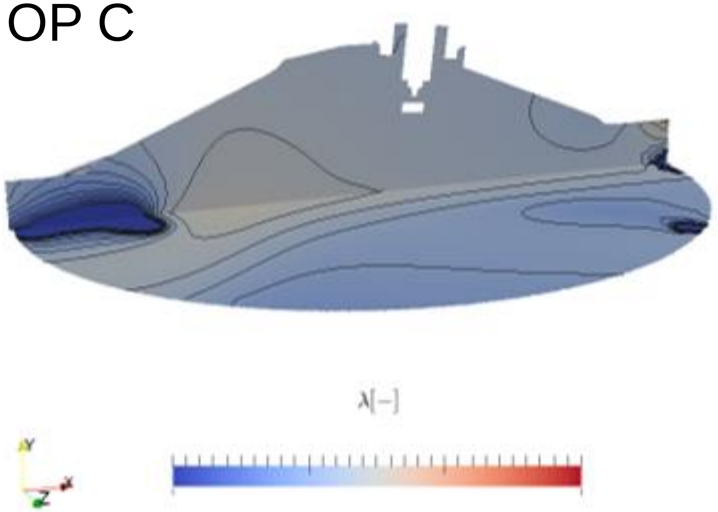
OP A



Increase engine speed

OP C

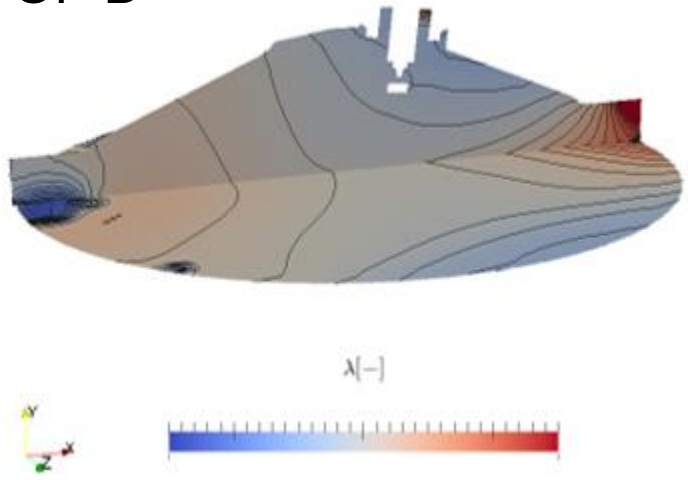
[1]



20° bTDC

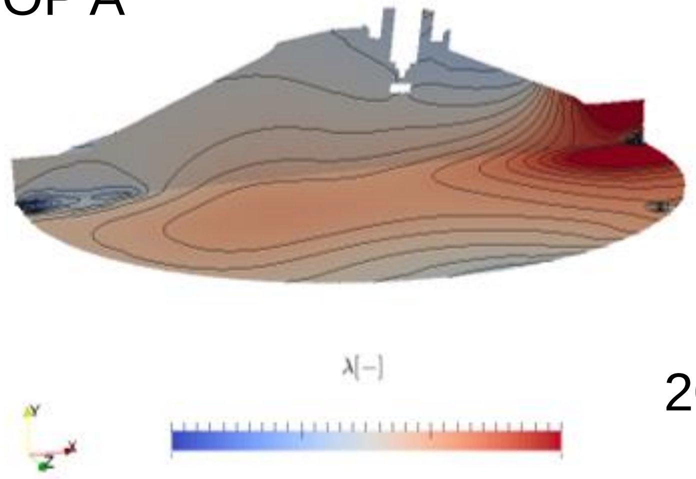
Reduction engine load

OP B



- Spray G injects insufficient amount of mass for optical engine
  - Longer injection time required for stochiometric mixture
- Charge stratified at low engine speed
- High engine speed reduces stratification
  →Turbulence dispersion of the charge

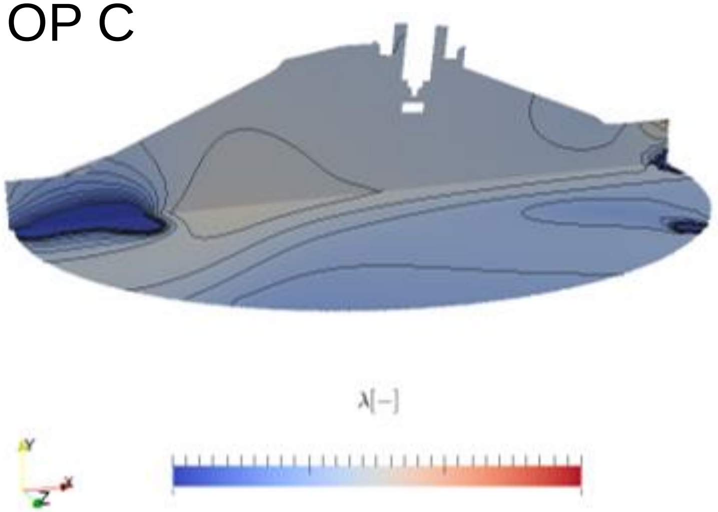
OP A



Increase engine speed

OP C

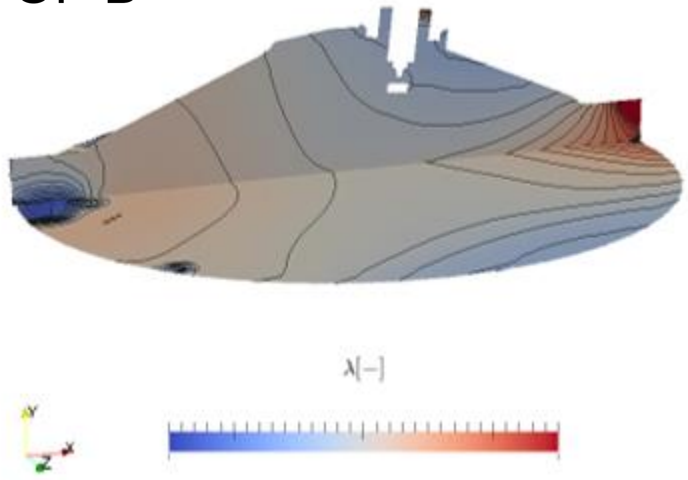
[1]



20° bTDC

Reduction engine load

OP B



- Rich zone on piston under intake valve plates
  - Large wall film evaporates
- Lean zone below exhaust valves
- Small and concentrated rich region at the crevice near exhaust valve
  - Wall film on liner enters the crevice during compression

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CONCLUSION

- Simulation of all 4 motored operating point of Darmstadt engine was performed with OpenFOAM
- Velocity fields and pressure was compared against experimental data showing good agreement
- Darmstadt optical engine coupled with ECN Spray G3 was simulated
- Influence of engine load and speed on the fuel/air mixture formation was studied
  - Engine speed reduce stratification
- Large region of wall film formation can be observed
- Wall film has large impact on fuel air mixture distribution

OUTLOOK

- LES study of multiple cycle
- Study the influence of wall-gas-spray interaction
- Study the motored condition with alternative turbulence model (like IIS-RSM)

Acknowledgment

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