Modeling Partially Premixed Combustion in a Light Duty Optical Diesel Engine

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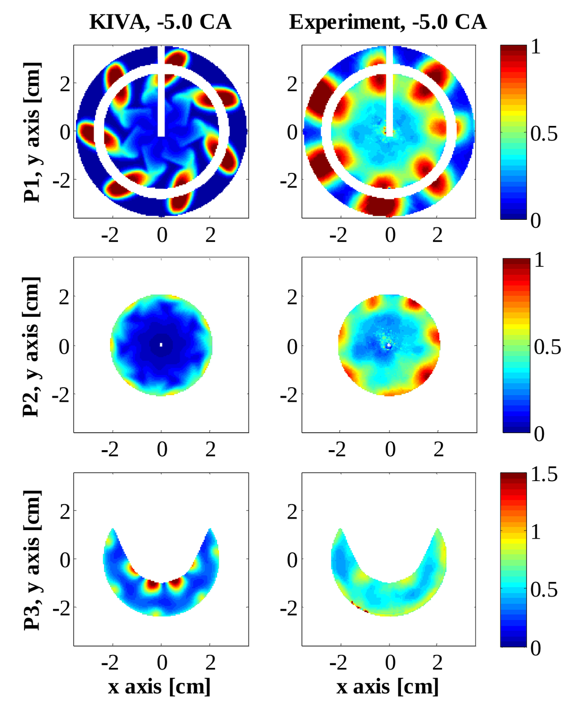
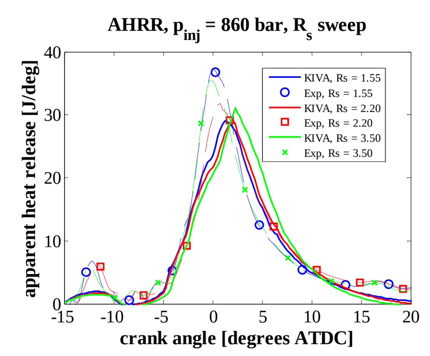
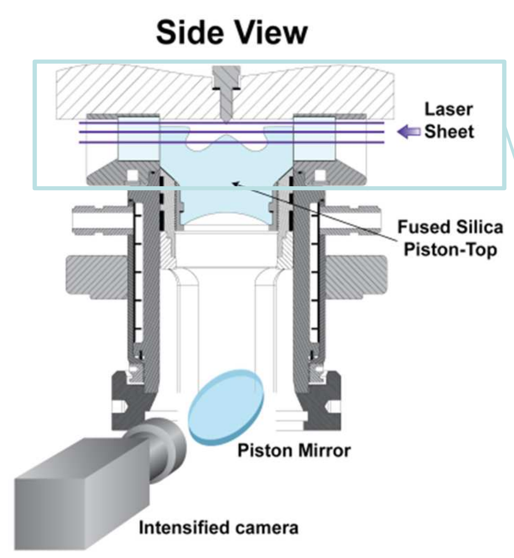
Motivation

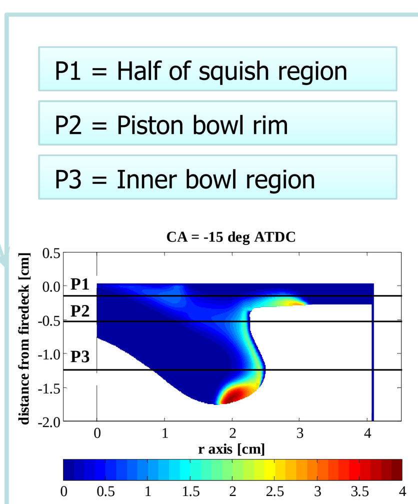
- Partially premixed compression ignition combustion allows very low engine-out PM and NOx emissions, and is a candidate optimal combustion strategy for low-load engine operation through highly dilute intake charge composition, slightly boosted pressure and early injection timing
- Sector mesh engine simulations achieve an extremely good match with the experimentally measured equivalence ratio distributions, but they are not able to properly capture air-fuel mixing in the central part of the combustion chamber and in the piston bowl
- As an outcome, the overall timing of the ignition process is very well captured by the trends are still far from the experimental values
- Improved modeling is needed to capture the crucial interaction between mixing and chemical kinetics





Experimental setup





Engine specifications

Bore x stroke [mm]	82.0 x 90.4
Unit displacement [cm^3]	477.2
Compression ratio	16.4 : 1
Squish height at TDC [mm]	0.88

Bosch CRIP 2.2 Injector

Sac volume [mm^3]	0.23
Number of holes	7
Included angle [deg]	149
Hole diameter [mm]	0.14
Hole protrusion [mm]	0.3

Fuel properties

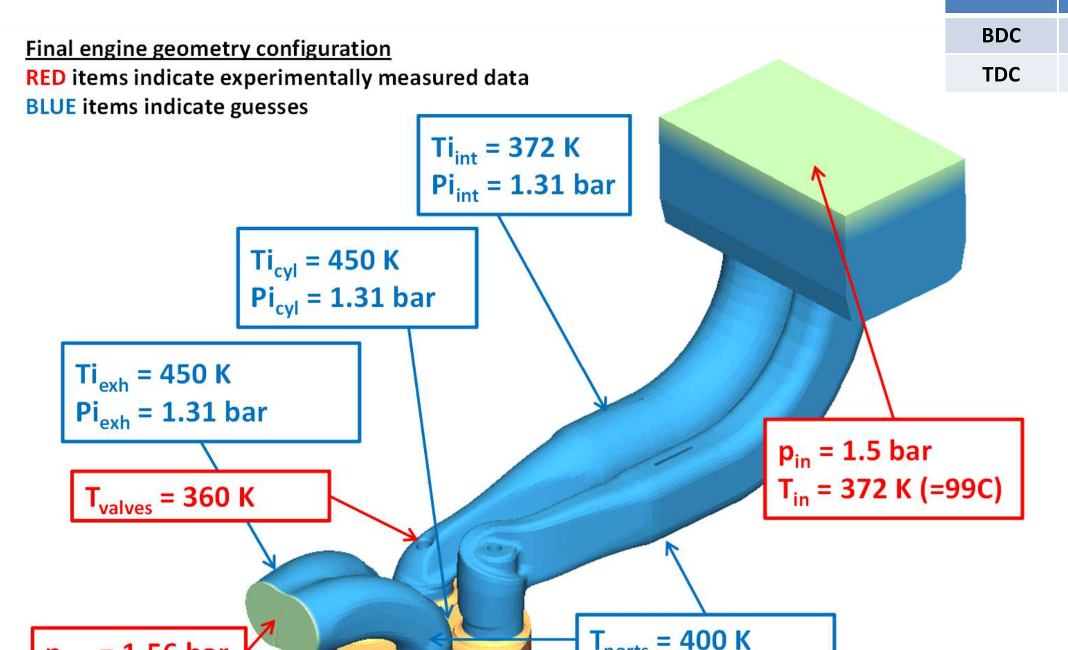
Composition [mole fractions]	75% nC_7H_{16}
	25% iC_8H_{18}
Fluorescent tracer [mass fraction]	0.5% C_7H_8
Equivalent Cetane Number	47

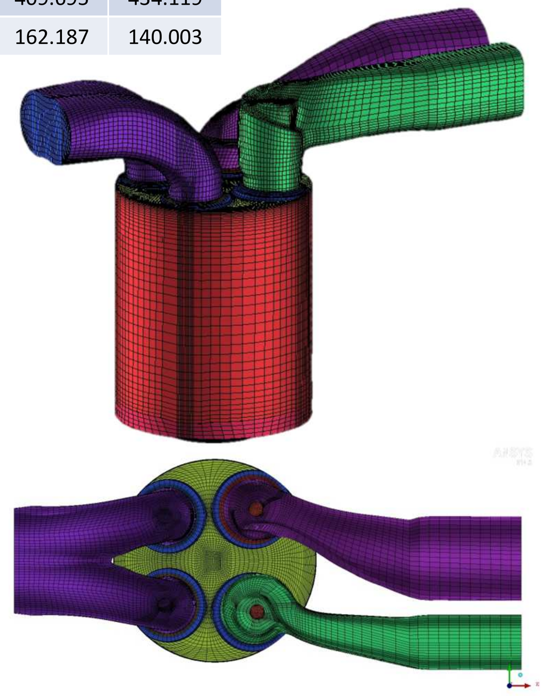
- Single-cylinder, optically accessible light duty diesel engine retaining the geometry of the production engine (GM 1.9L)
- PLIF imagery excited by a 266nm UV horizontal laser sheet
- Multiple ensemble-averaged images at three planes within the combustion chamber and CA = [-17.5:2.5:-5.0] deg ATDC

Full Engine Geometry Modeling

- A full 360 degrees unstructured engine mesh including intake runners and exhaust duct has been generated to study the effects of engine geometry on fluid flow motion, spray dynamics, and combustion.
- The unstructured grid allows high-quality computational cells throughout the domain, leading to improved wall boundary treatment, internal flow modeling through the valves and solver convergence.
- Cells in the near-nozzle region maintain regular aspect ratio

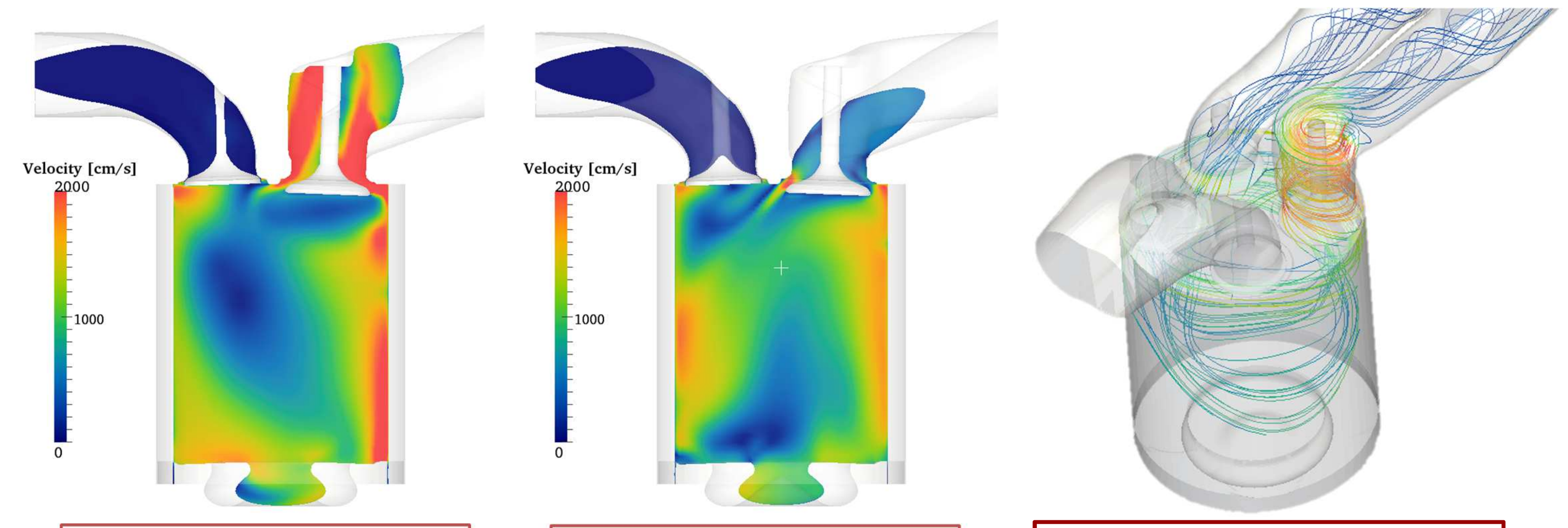
	ncells	nverts
BDC	409.695	434.119
TDC	162.187	140.003





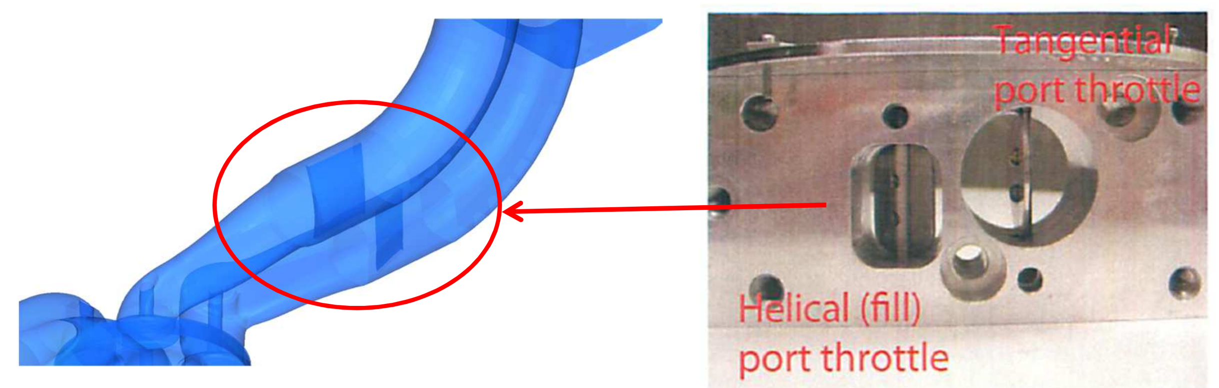
Fluid Flow motion and swirl modeling

- Modelling of the intake duct geometry is essential to capture the fluid flow structure in-cylinder as the two intake ducts play different roles: the tangential port pushes the flow downwards and towards the cylinder liner, while the helical port increases momentum more locally, impacting the final swirl ratio



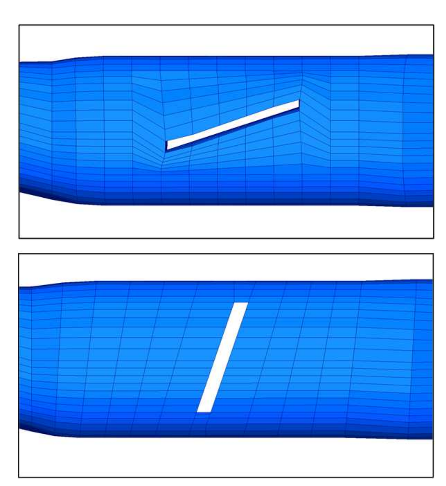
Helical port section — Tangential port section — Velocity streamlines at BDC during intake

- In the experiments, different **swirl ratios** are imposed by throttling the intake ports
- **Throttles** in the intake ports are modeled deactivating and orienting a layer of cells to the throttle plate angle



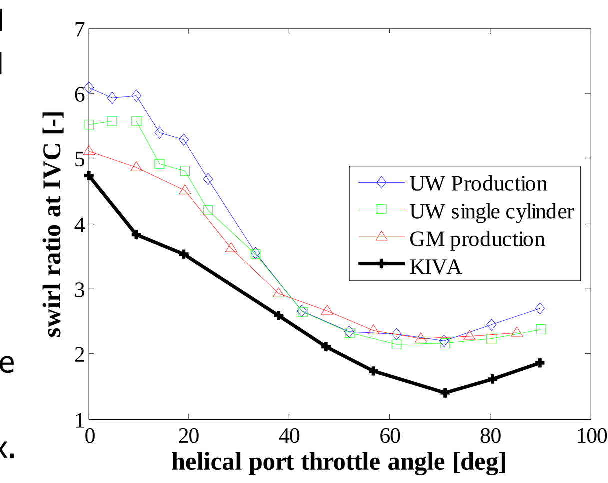
Pin	0	19
Throttle	Fully closed	Fully open

- A Matlab code has been developed to accordion the original mesh to the actual throttle positions, to prevent cells from colliding or becoming non-convex

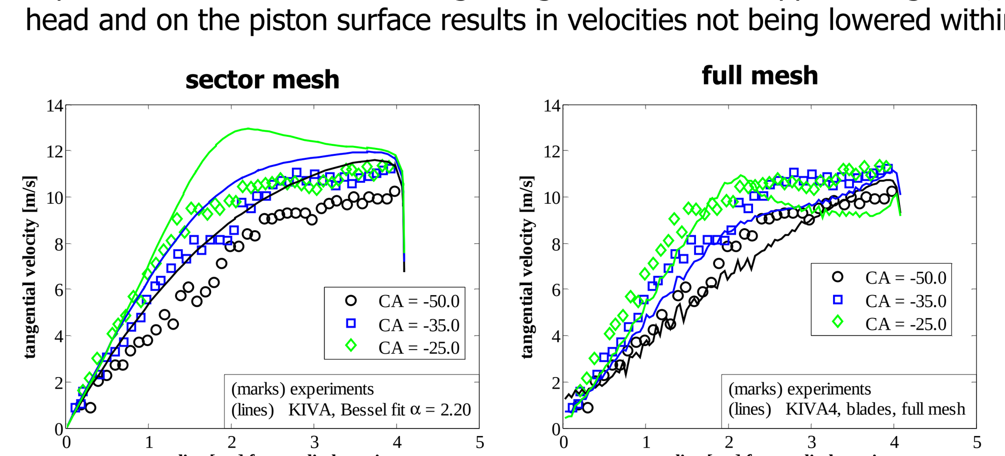


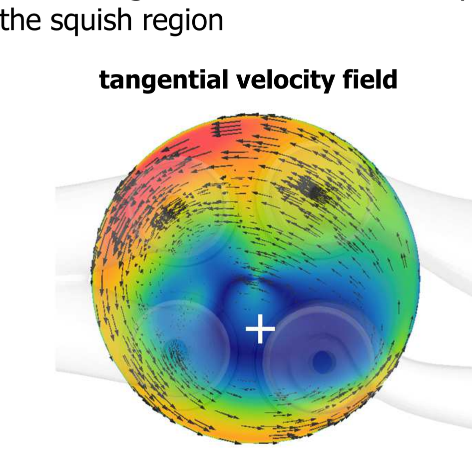
🡐 Figure shows helical port throttled to pin 15 (-71.05 degrees) (top), and throttled to pin 4 (-18.95 degrees) (bottom)

The IVC swirl trend matches very 🡒 well the open-end swirl ratio measurements on the engine. Rs at IVC is however consistently smaller than the open-end measurements, as piston velocity at that point is not at its max.

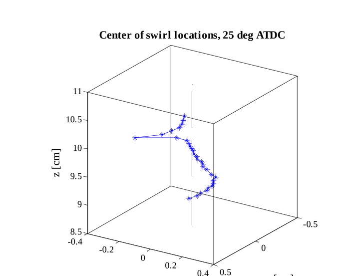


- Even if the predicted swirl ratio value is smaller than the measured number, the full engine geometry better captures tangential (swirling) velocity flow field structure near the cylinder head: sector mesh predictions initialized with the experimental Rs number show high tangential velocities approaching TDC, and lack of geometric details in the cylinder head and on the piston surface results in velocities not being lowered within the squish region



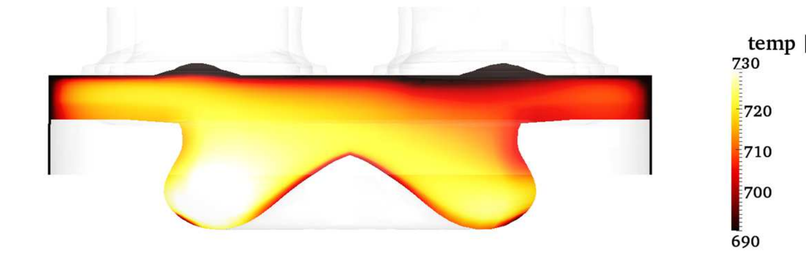


CA = 25 deg ATDC, 3mm below firedeck



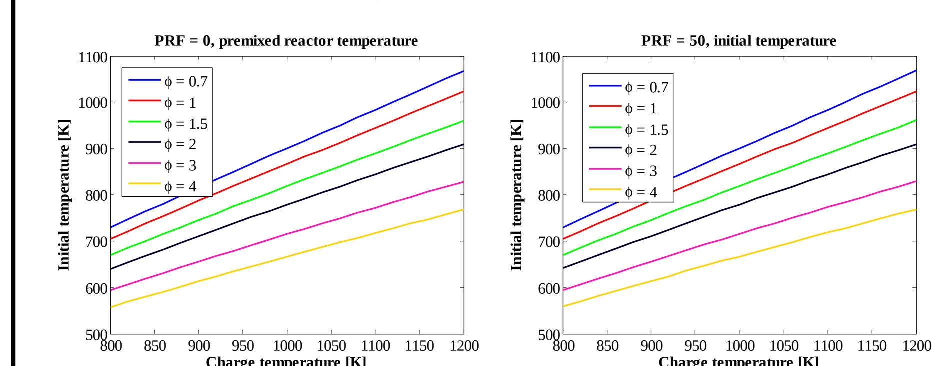
🡐 The RANS flow solver is capable to capture non-axisymmetric structure of the swirl vortex at different axial positions within the combustion chamber as long with its tilt and precession during the compression stroke. Validation against in-cylinder PIV measurements is necessary

- The flow field non-uniformity has an impact also on the **temperature field** – at typical PPC injection timings, 25 degrees before TDC, temperature stratification in the piston bowl is of about 25K even during motored engine operation



Phi-sensitivity of the reaction mechanism

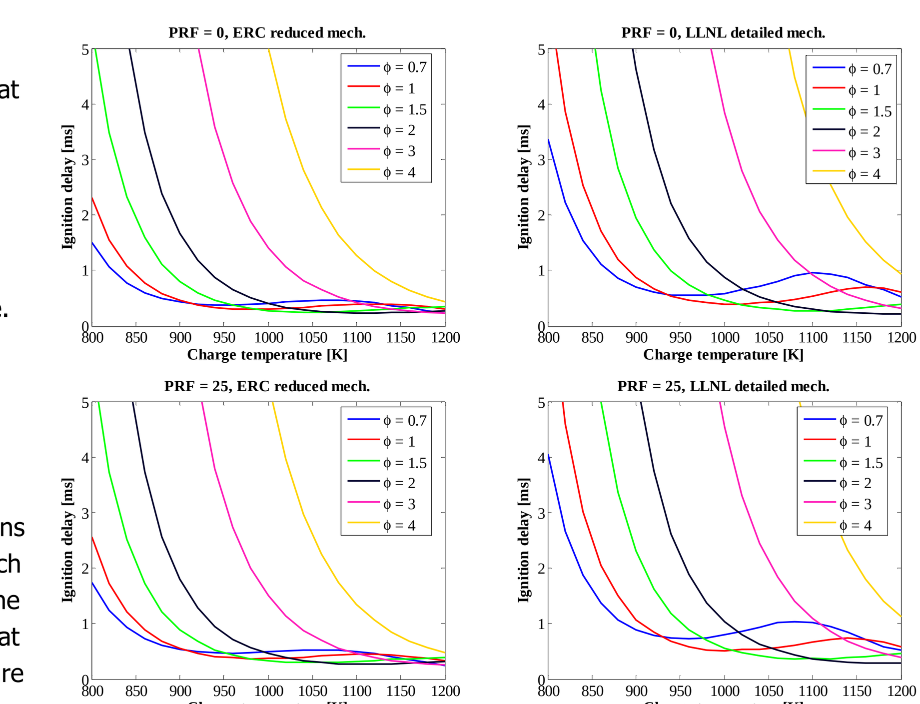
- An investigation to compare the ϕ sensitivity of the ERC PRF mechanism (Ra and Reitz, Comb Flame 2008) with the detailed LLNL PRF mechanism (Curran et al., Comb Flame 2002), and test their ability to capture ignition at a range of fuel compositions and fuel/air equivalence ratios in-cylinder.
- **Ignition delay** calculations are setup at engine-like conditions: $\phi \in \{0.7, 1.0, 1.5, 2.0, 3.0, 4.0\}$, $T_{charge} \in [800, 1200]\ K$, $p = 50\ bar$, $T_{fuel} = 363K$
- To capture fuel effects on ignition, we consider the fuel's **evaporative cooling** process by simulating the fuel vaporization and mixing process into the charge, using real liquid and gas-phase mixture properties



- **Charge cooling** due to fuel evaporation and mixing can be increased by about 130 K at stoichiometric conditions, up to about 350 K at very rich (ϕ = 4) equivalence ratios
- **Equivalence ratio**, more than fuel composition, is the driving factor on charge cooling 🡒 it is important to capture local equivalence ratio behavior in both the CFD domain and as far as the ignition process (chemistry domain).

- An **experimental pilot ignitability study** has shown that a minimum temperature of about 820K is needed to ignite a 1mg pilot injection with low EGR rates
- When simulating pure n-heptane, the reduced mechanism captures ignition for lean mixtures at LTC conditions. Smaller ignition delays are predicted than the detailed one.
- Then simulating PRF25, the reduced mechanism shows a reliable trend towards lower reactivity and higher ignition delays

The reduced mechanism is developed for engine simulations end its early ignition delay timings mirror the need to match not only shock tube and flame experiments, but also engine combustion cases where temperature stratification and heat transfer play a fundamental role and are difficult to measure



Conclusions and Future Work

- Geometric details play a fundamental role on the operation of small, light-duty engines
- Validation of spray models for the unstructured solver is necessary to study the impact of engine geometry and non-axisymmetric fluid flow on differences among the spray jets, and ultimately on in-cylinder emission sources
- Multi-cycle simulations can help understand the flow field dependency on the previous cycle outcome
- The computational expenses of detailed engine models are still too much demanding for practical engine design simulations 🡒 full fluid flow solver parallelization as well as sparse chemistry modelling and chemistry cell grouping are needed for reducing the simulation requirements