FIAT CHRYSLER AUTOMOBILES

POLITECNICO DI TORINO
Dipartimento Energia

Analysis of Water Injection Potential for Knock Mitigation

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CONVERGE USER CONFERENCE – EUROPE - 2018
Savoia Hotel Regency - Bologna, Italy
March 19 – 23, 2018

Acknowledgements

POLITECNICO DI TORINO
Dipartimento Energia

- Federico Millo
- Mohsen Mirzaien

FCA FIAT CHRYSLER AUTOMOBILES | CRF

- Caterina Venezia
- Andrea Stroppiana
- Massimo Ferrera
- Francesco Vattaneo

STSe srl

- Lucio Postrioti

Agenda

- Introduction
- Experimental activity
- CFD-3D Model and Validation
- 3D-CFD Optimization of Water Injection Configuration
- 0D/1D Combustion Simulation and Knock Prediction
- Conclusions

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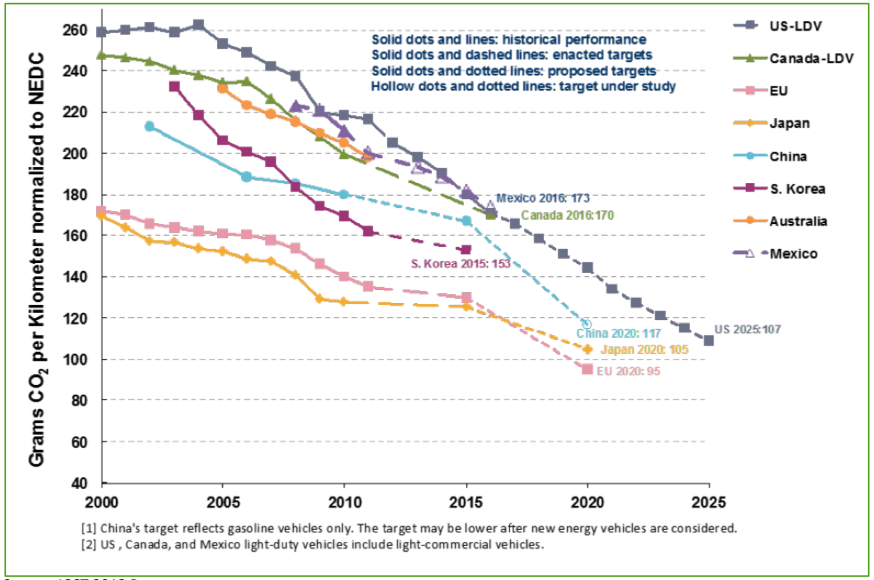
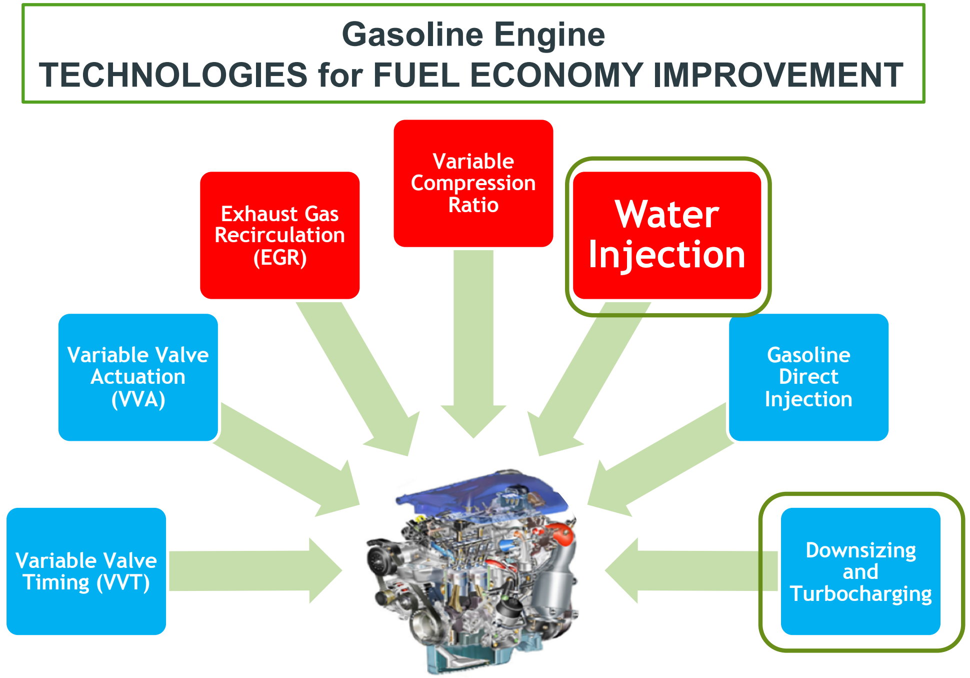
Introduction

Legislations worldwide are converging to long-term fuel economy and CO_2 emissions targets of below 100 g/km, hence invoking the necessity of utilizing advanced technologies in SI engine development with a synergic approach.

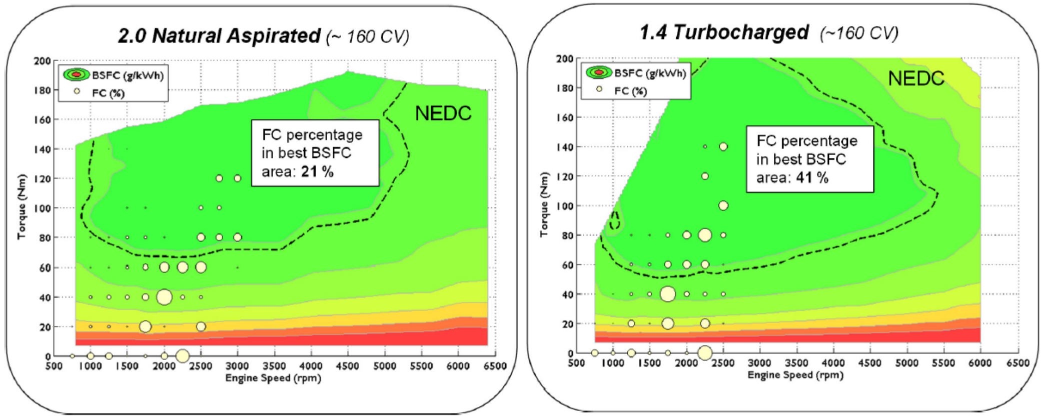


Source: ICCT 2013 Report

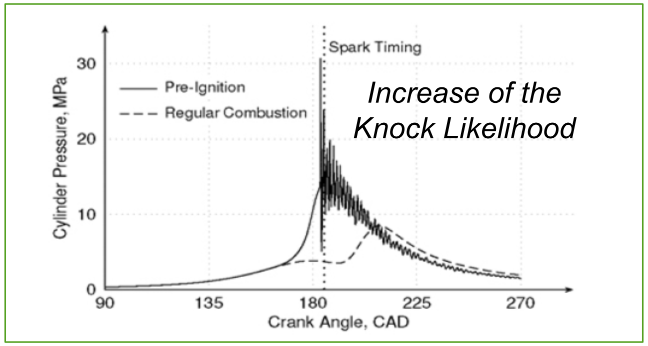


Introduction

DOWNSIZING example



Source: Luisi S., Doria V., Stroppiana A., "Knock Mitigation Techniques for Highly Boosted Downsized SI Engines", in Proc. CO2 reduct. transp. Syst. ATA/SAE Int. Conf., Turin, Italy, 2017



Source: C. Dahnz, at al., "Investigations on Pre-ignition in Highly Supercharged SI Engines", SAE Int. J.Engines 3(1):214-224, 2010, doi:10.4271/2010-01-0355

KEY ENABLER for DOWNSIZING

↓

TURBOCHARGING

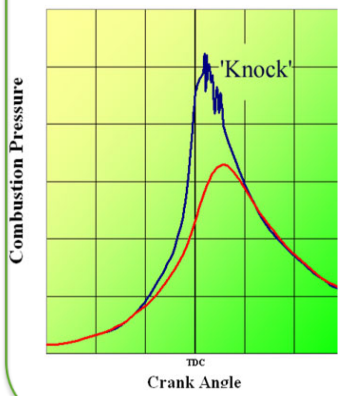
DRAWBACK: high boost level is required to compensate the lower engine displacement and maintain a favorable torque output an

↓

increase of knock likelihood at medium / high engine load

Introduction

KNOCK ISSUE



CONS

- Fuel Enrichment
- Retarded Spark Timing

Fuel Economy Deterioration

New Technologies

KNOCK MITIGATION

Both simulation and experimental studies are necessary in order to:

- Develop **predictive models** capable to capture the effects of knock mitigating techniques such as water injection on both **combustion** and **knock;**
- **Maximize the benefits of water injection and minimize** possible **disadvantages** (oil dilution, incomplete water evaporation, etc);
- Estimate **water tank size** and **fuel consumption** benefits over different **driving cycles,** such as **NEDC**, **WLTC, US06** and **RDE.**

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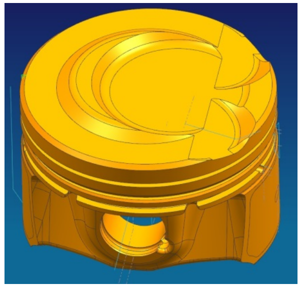
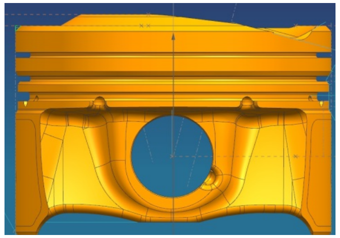
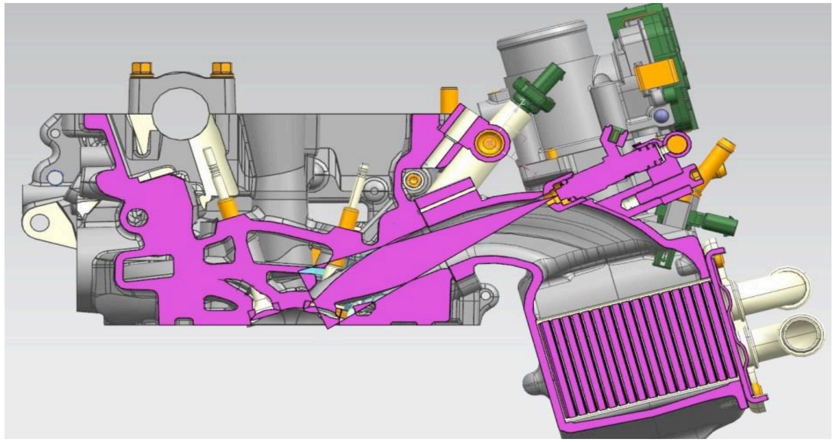
Experimental Activity

- An experimental research activity was carried out on small displacement turbocharged engine equipped with Gasoline Direct Injection and a water injection system.
- Water injectors have been installed into intake manifold runners (Port Water Injectors).
- Two different configurations of the engine were tested:
  - CR = 10
  - CR = 13 w/ water injection.





Piston CR=13

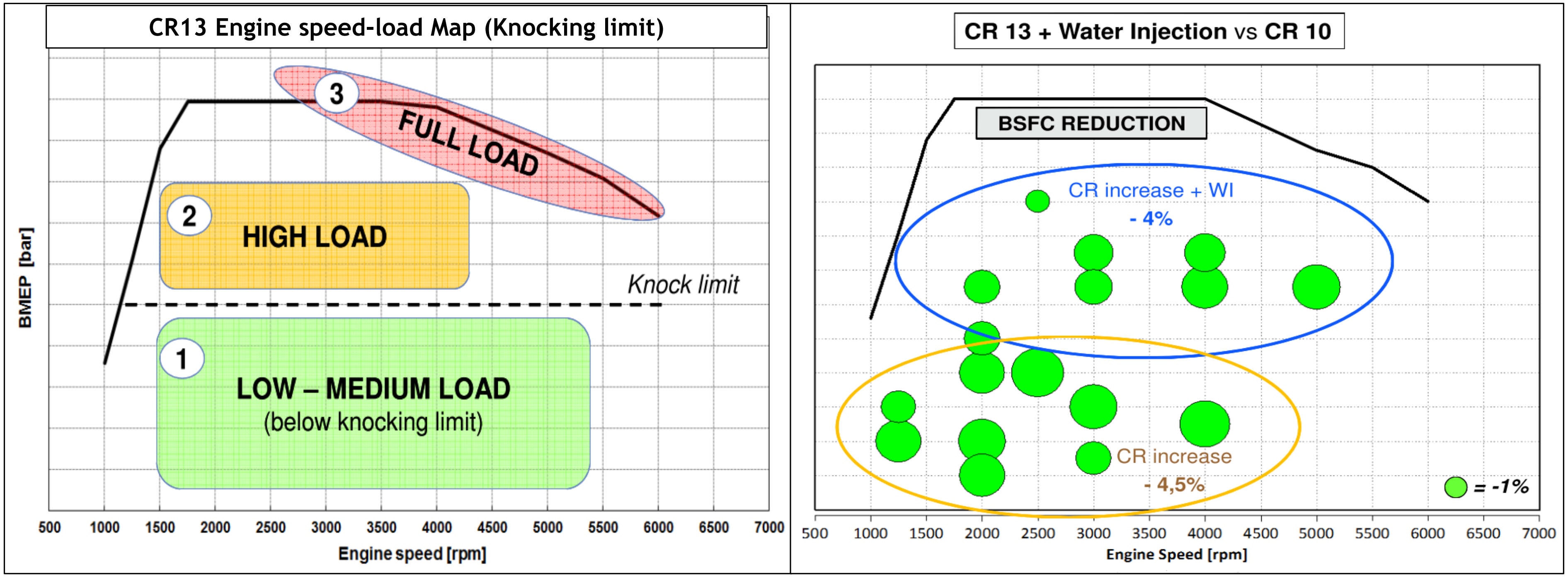


Layout of engine head, intake manifold, and runner with water injector

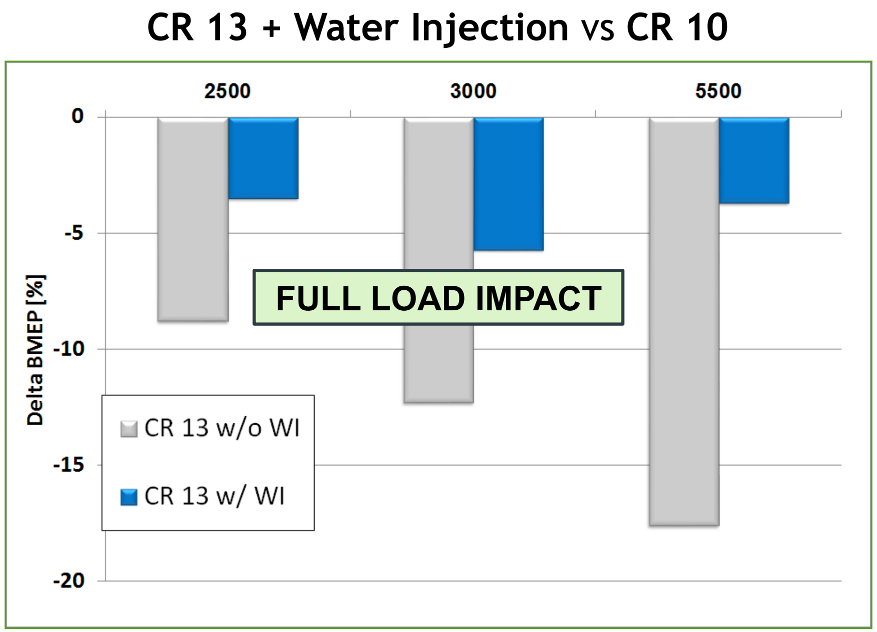
*Source: Luisi S., Doria V., Stroppiana A., “Knock Mitigation Techniques for Highly Boosted Downsized SI Engines”, in Proc. CO2 reduct. transp. Syst. ATA/SAE Int. Conf., Turin, Italy, 2017

Experimental Activity

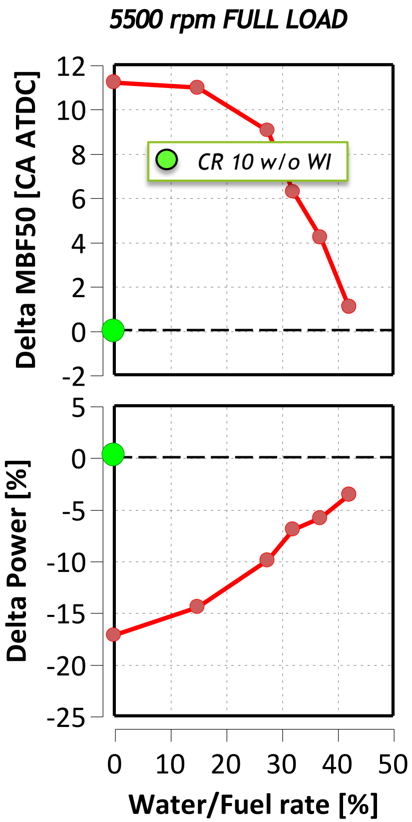
- Target of increased CR: improve engine efficiency over the whole engine operation map (even below the typical knocking zone) for CO_2 emission reduction, maintaining good performance level.



Experimental Activity



WI allows to use higher CR (13) with limited penalties on PERFORMANCE



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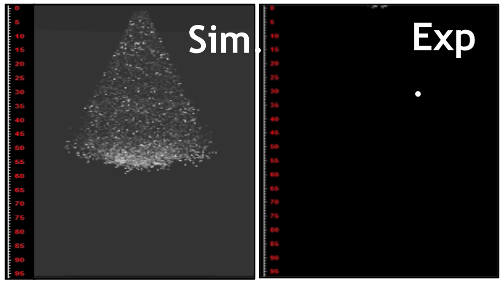
CFD-3D model and validation

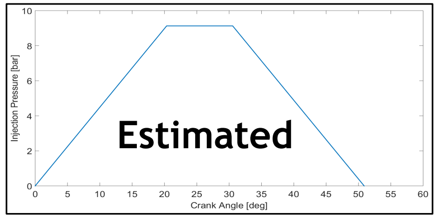
Water spray

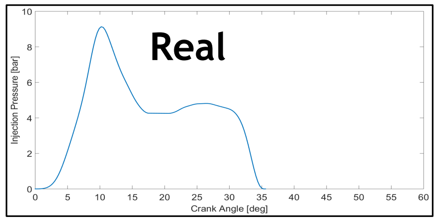
- To improve the model accuracy the real water injection flow rate and the water spray pattern have been experimentally measured and reproduced in Converge v2.3, at **two different injection pressures** (6 bar / 9 bar).

Numerical setup (spray bomb)



Water spray pattern calibration:
simulated Vs experimental

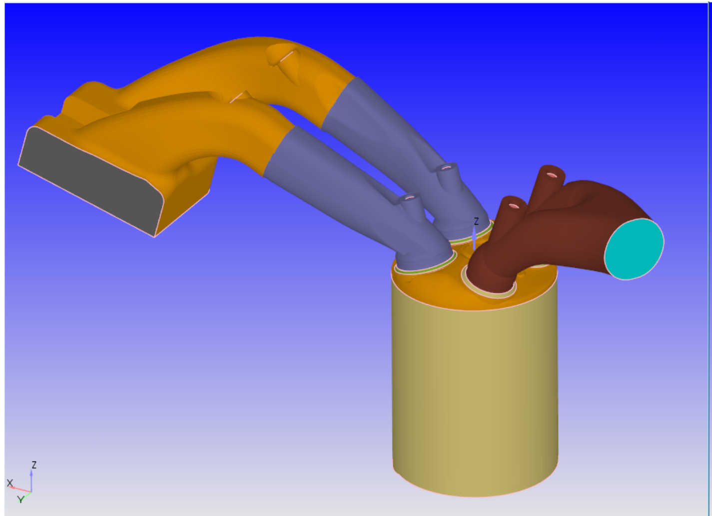




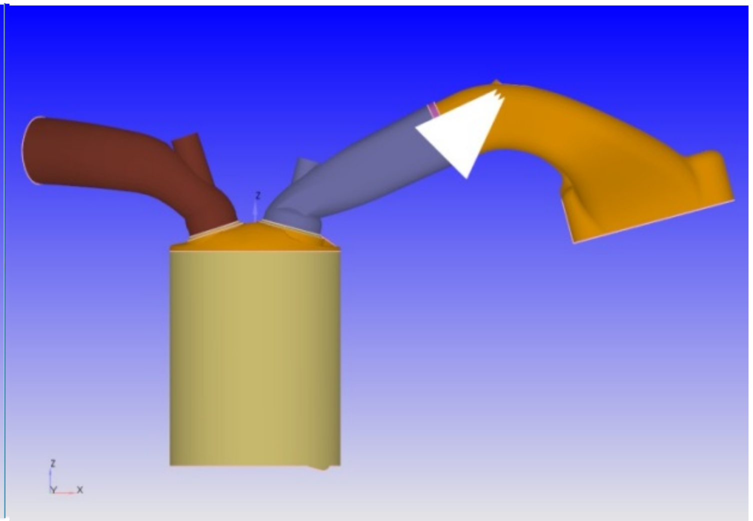
- KH+RT breakup models (w/o breakup L)
- Discharge coefficient model enable (w/ Cv corr.)
- Calibration of:
  - breakup time constant
  - model size constant
  - Nozzle discharge coeff. (inj. Pressure)
- Sensitivity analysis on mesh and parcel n., final setup:
  - Base grid size = 2 mm
  - Fixed embedding + AMR on velocity and temperature (min cell size 0.25 mm)
  - 150k parcels/nozzle

CFD-3D model and validation

Engine model



Iso view



Water injector orientation

Millerization w/ late intake valve closure → Backflow (spray+gas) → Intake runners included in CFD-3D

CFD-3D model and validation

Setup (Converge v2.3):

- Multi-cycle analysis (stabilization of water film in intake ports) w/o combustion (customized mapping/init.)
- RANS turbulence: k-eps RNG (default coeff.)
- O'Rourke ad Amsden wall heat transfer model
- Spray simulation water + gasoline (IC8H18 fuel)
- O'Rourke spray turbulent dispersion, NTC collision, Dynamic drop drag
- O'Rourke wall film model w/ film strip enabled (default coeff.)
- Base grid size = 2 mm
- AMR (velocity, temperature) customized. Min cell size = 0.25 mm (intake ports, cylinder)
- Boundary AMR set to achieve y+ = 40÷100 especially on intake ports and valves
- Custom fixed embedding (injectors, cylinder, valves, etc.)
- UDFs for customized output

(Grid size, AMR, Boundary AMR and fixed embedding items: $N_{cells,max}$ = 2.5e6)

CFD-3D model and validation

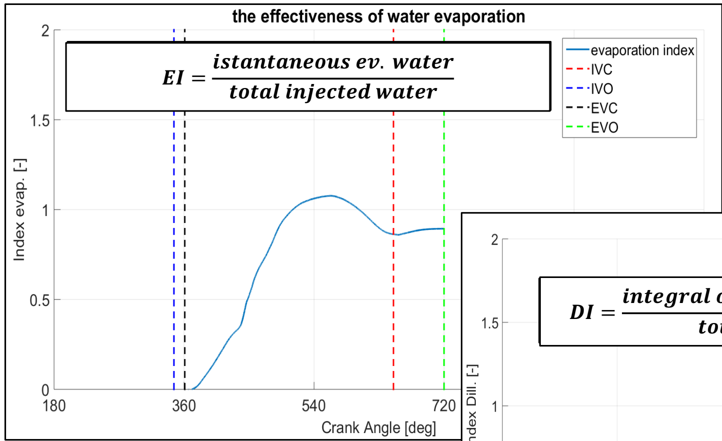
3D-CFD model capabilities in predicting water evaporation and the risk of engine oil dilution were assessed by comparing simulation results with experimental data @ **4000rpmxWOT**.

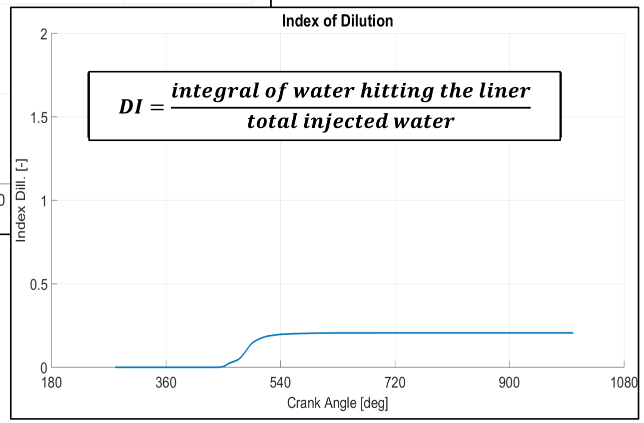
A sensitivity analysis was performed by acting on the following WI calibration parameters:

- Injection pressure (6/9) [bar]
- End of injection (360/450) [CAdeg]
- Water to fuel ratio (18.5/50) [%]
- Number of injectors/cyl. (2/1)

New CFD-3D indexes were specifically defined:

- **Evaporation Index (EI)**
- **Dilution Index (DI)**





They were used to compare the effectiveness of water injection for different layouts and calibration parameters.

CFD-3D model and validation

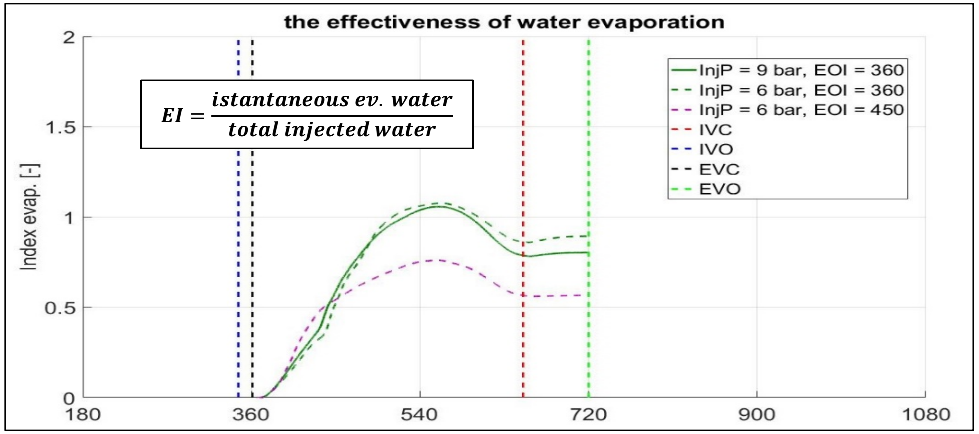
WI calibration parameters:

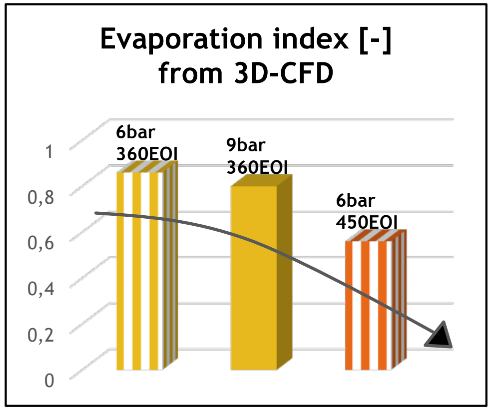
- **Injection pressure (6/9) [bar]**
- **End of injection (360/450) [CAdeg]**
- Water to fuel ratio (**18.5**/50) [%]
- Number of injectors/cyl. (**2**/1)

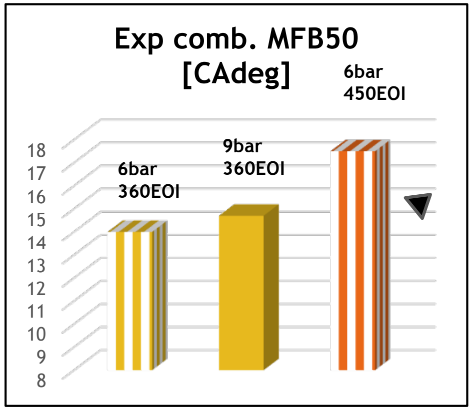
Water evaporation effectiveness is strictly related to combustion phasing, since the higher the percentage of vaporized water during intake, the lower the mixture temperature during compression and thus the less retarded combustion (lower MBF50 AFTDC).

Takeaways from 3D-CFD:

- **Injection Pressure has negligible effects** on water evaporation effectiveness.
- **Injection Phasing is important:** EOI@360CAdeg allows increasing the water dragging into cylinders.







CFD-3D model and validation

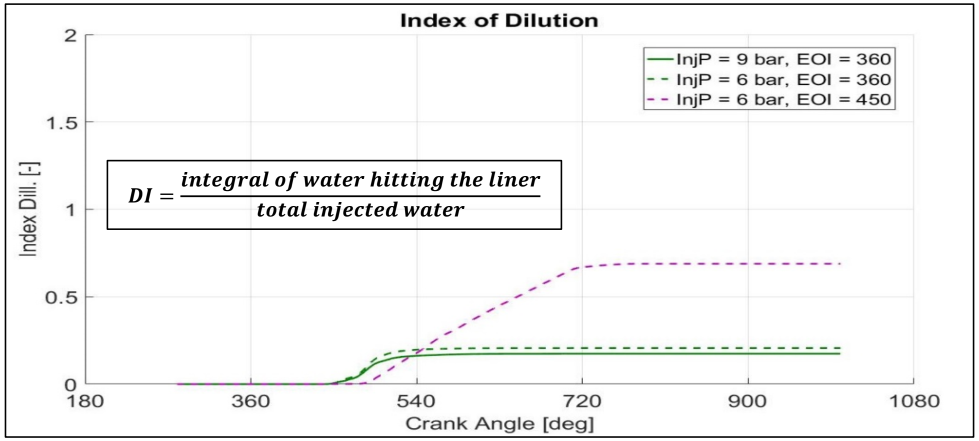
WI calibration parameters:

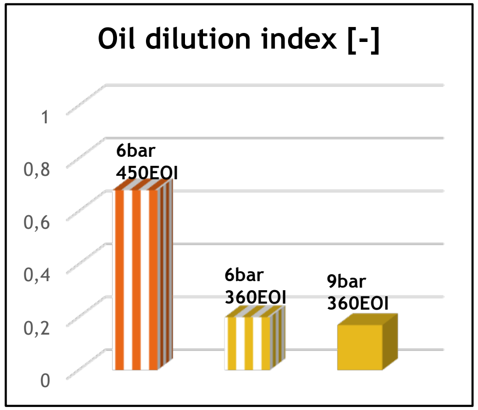
- Injection pressure (6/9) [bar]
- End of injection (360/450) [CAdeg]
- Water to fuel ratio (**18.5**/50) [%]
- Number of injectors/cyl. (**2**/1)

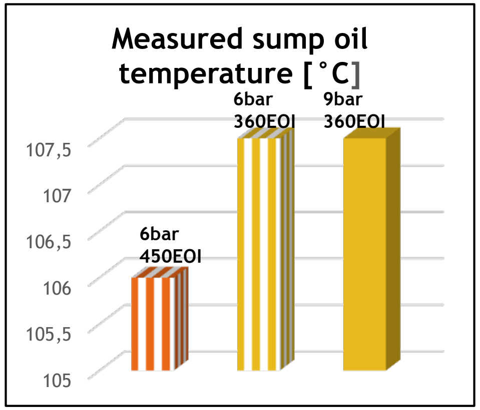
Water impingement on the liner and lube oil dilution can be related to the measured sump oil temperature since the higher the percentage of water hitting the liner, the higher the oil cooling effect.

Takeaways from 3D-CFD:

- **Injection phasing has crucial effect** on water impingement on the liner.
- EOI@360CAdeg allows the water to be dragged into the cylinder under reduced air flow speed conditions through the intake valves, minimizing the risk of lube oil dilution.







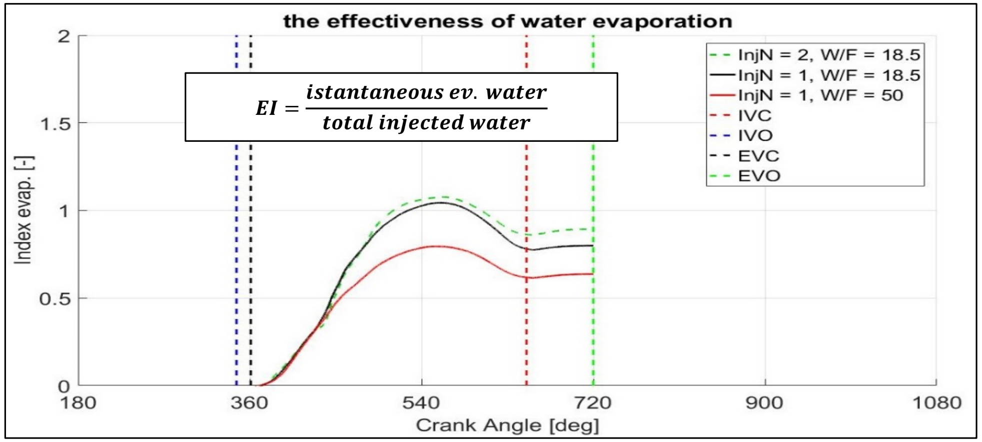
CFD-3D model and validation

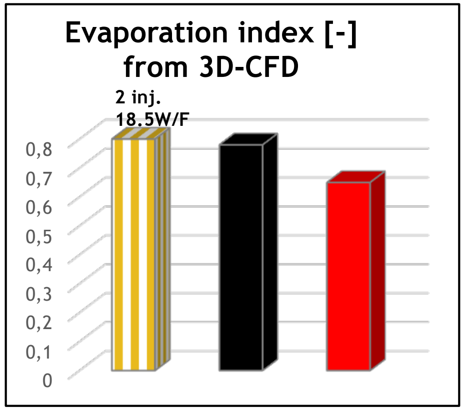
WI calibration parameters:

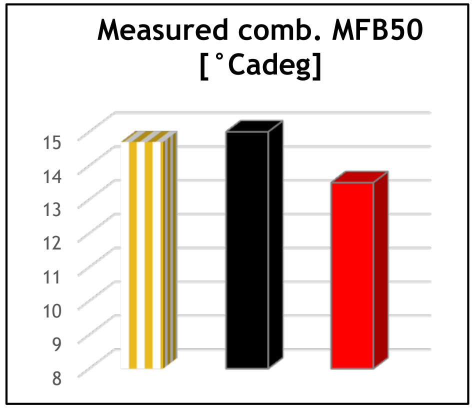
- Injection pressure (**6**/9) [bar]
- End of injection (**360**/450) [CAdeg]
- **Water to fuel ratio (18.5/50) [%]**
- **Number of injectors (2/1)**

Takeaways from 3D-CFD:

- **The number of injectors has negligible effect** on water evaporation effectiveness;
- W/F at 50% results in better combustion phasing. However, the injected water is almost tripled compared to the other two cases, with a lower evaporation effectiveness index ($\sim 0{,}6$) due to high water injection duration.

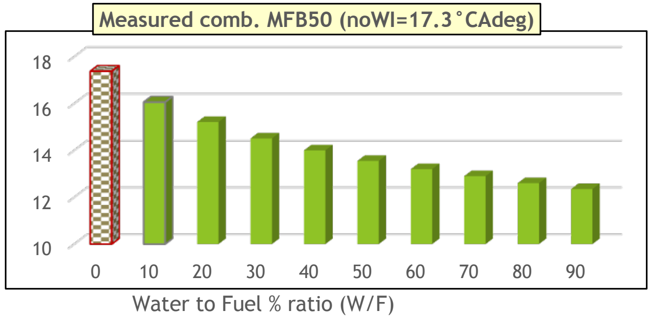


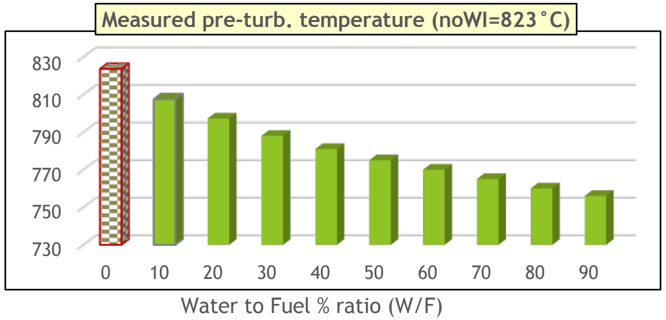


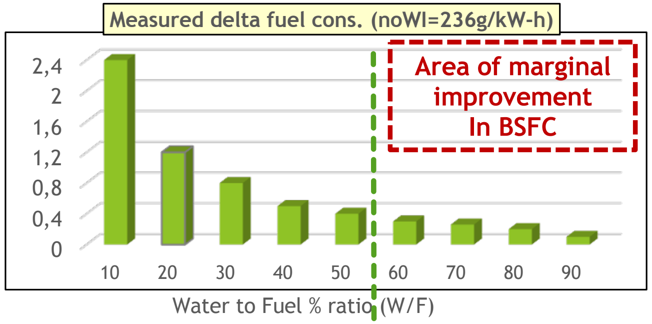


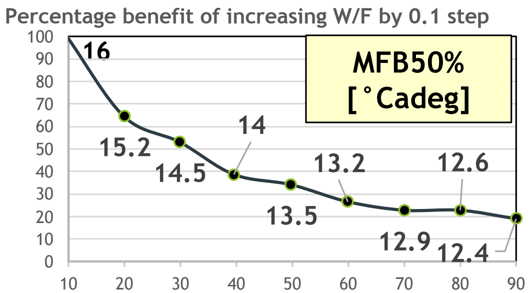
CFD-3D model and validation

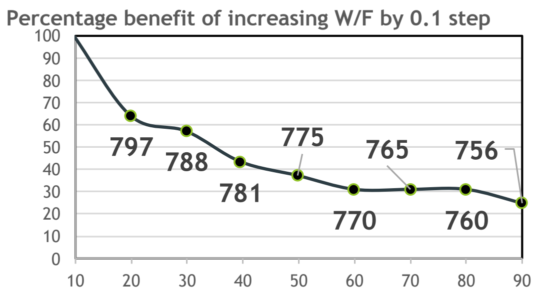
The reduced WI effectiveness at high W/F ratios observed via 3D-CFD simulations is in good agreement with experimental data: the higher is the W/F ratio, the lower is the reduction rate of MFB50, Turbine Inlet Temperature, and BSFC.
It can be noted that incremental improvements for either BSFC and TIT become negligible for W/F ratios higher than 50%, because of the reduced water evaporation effectiveness (as highlighted by 3D-CFD).

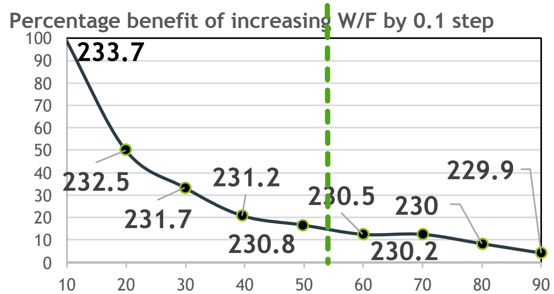












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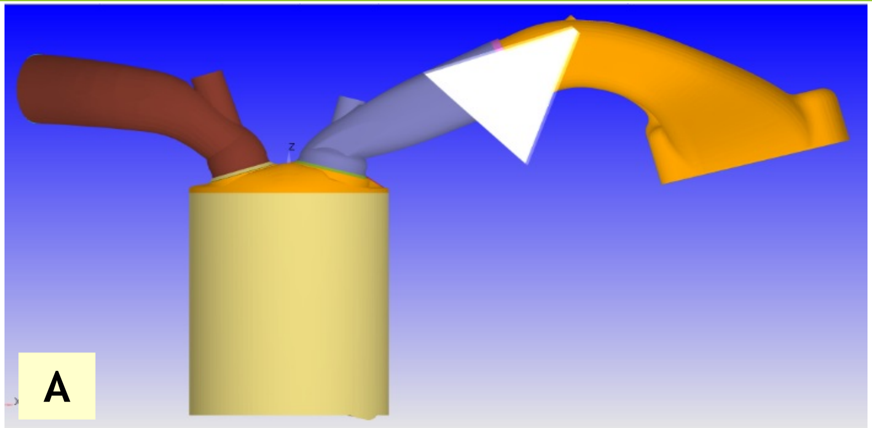
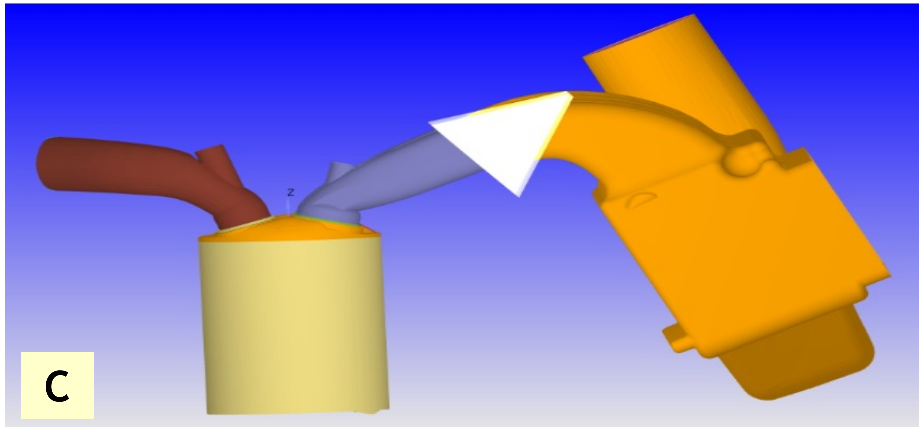
3D-CFD optimization of water injection configuration

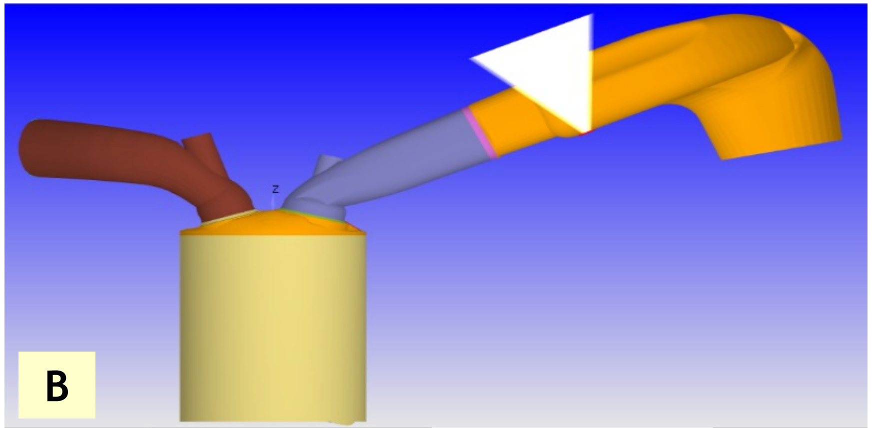
Once the model predicting capabilities were assessed and the evaporation index robustness was proved through the comparison with experimental data, a preliminary optimization of the WI layout among three different configurations (A, B, and C) was performed in 3D-CFD.



Injection from the top with parallel flow



Injection from the top with parallel flow and new integrated WCAC manifold



Injection from the bottom with perpendicular flow

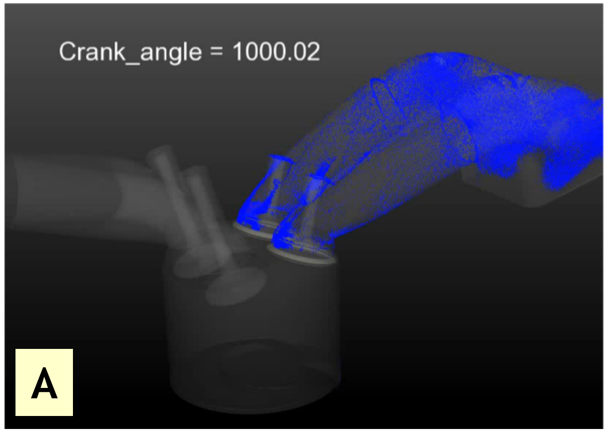
3D-CFD optimization of water injection configuration

Configuration A:
Injection from the top with parallel flow

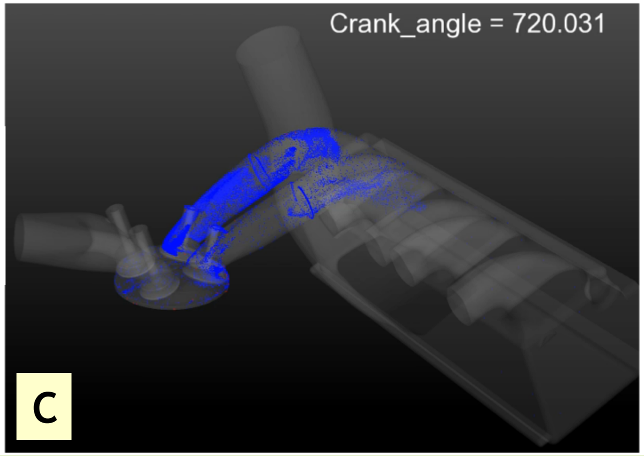
Configuration B:
Injection from the bottom with perpendicular flow

Configuration C:
Injection from the top with parallel flow and new integrated WCAC manifold

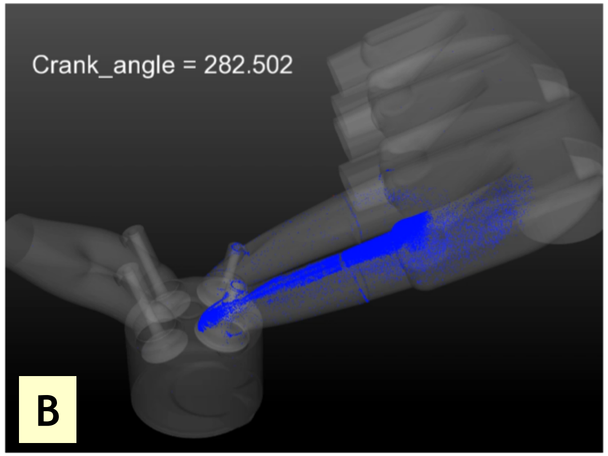
Inj. P= **6bar**
EOI= **360°CAdeg**
W/F= **18.5**
Inj = **2**



Inj. P= **6bar**
EOI= **360°CAdeg**
W/F= **18.5**
Inj = **1**

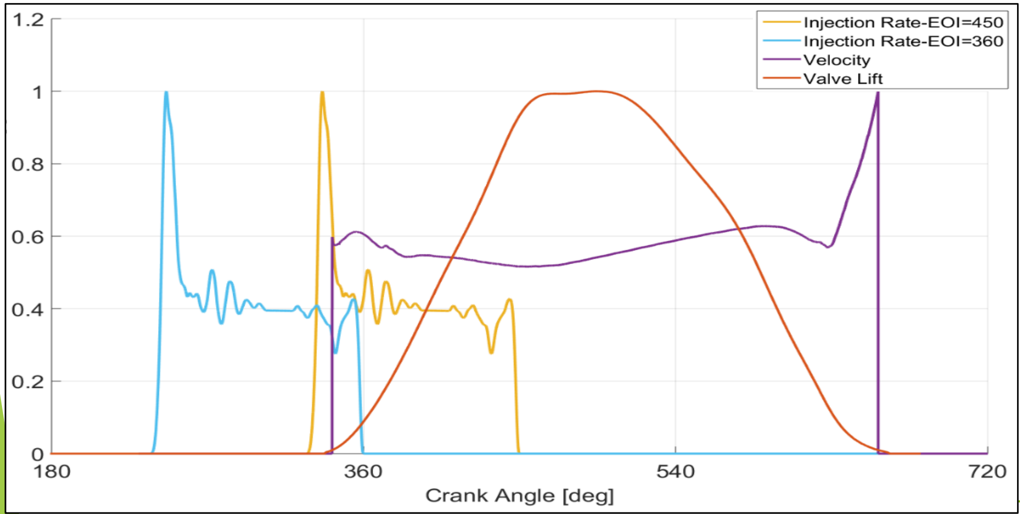


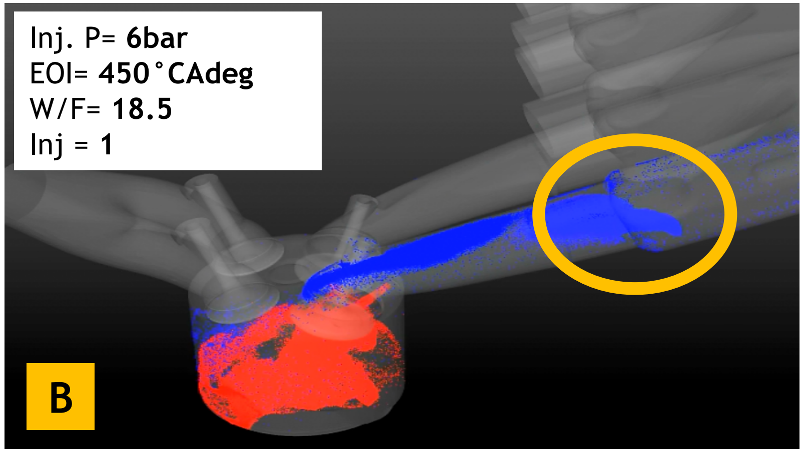
Inj. P= **6bar**
EOI= **360°CAdeg**
W/F= **18.5**
Inj = **1**

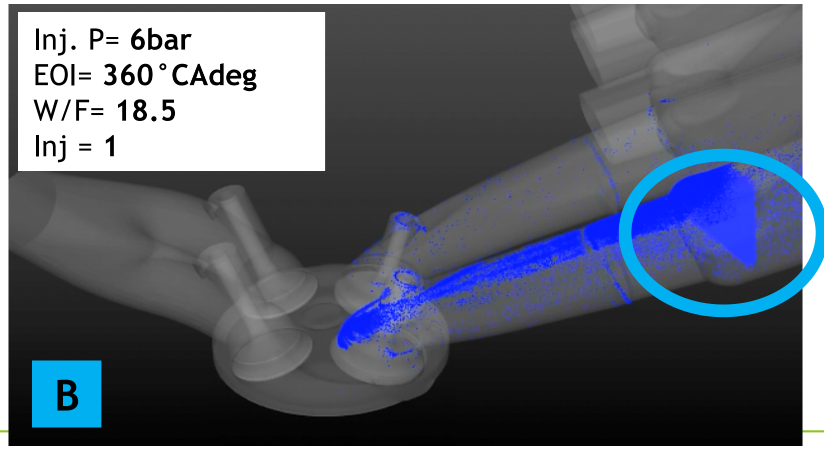


3D-CFD optimization of water injection configuration

In case of WI from the runner bottom with perpendicular flow, the EOI @450 CAdeg results in a better water dragging into the cylinder, since WI largely occurs after IVO so that high air flow speed deflects water particles pattern preventing them from hitting the port walls.

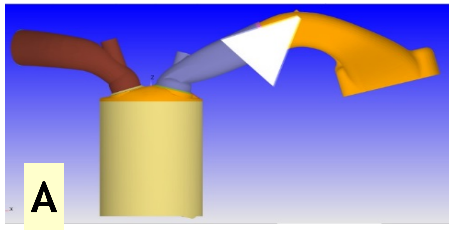


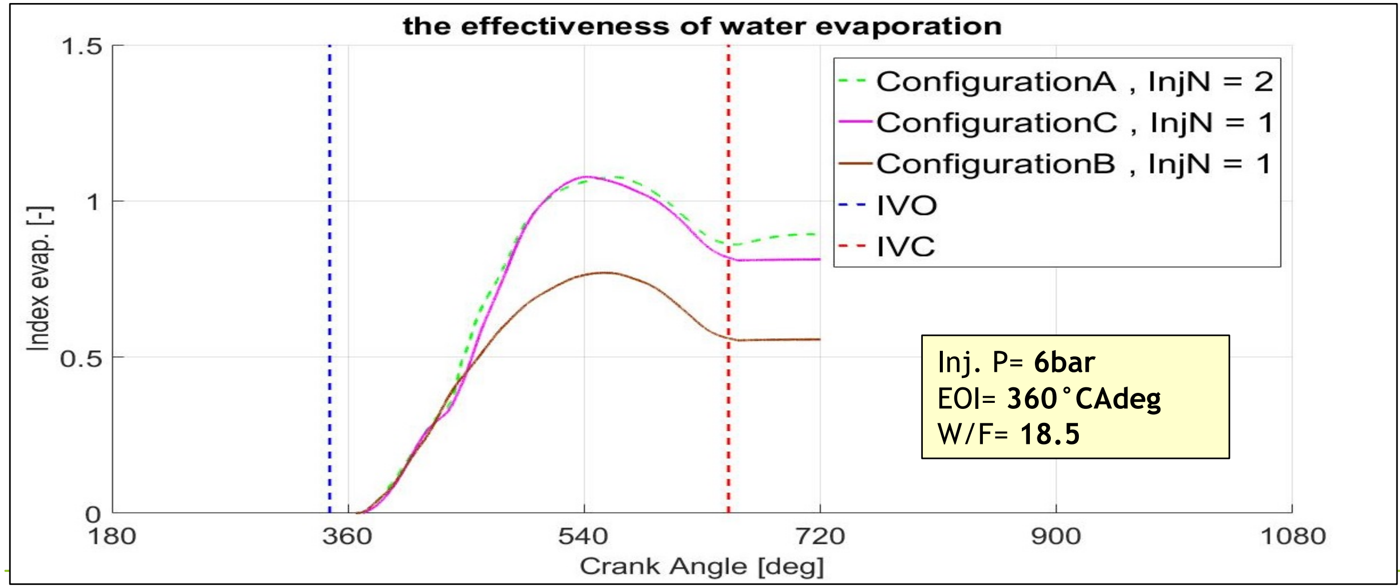


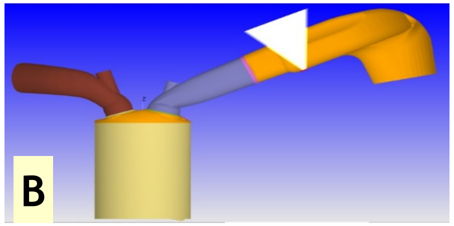


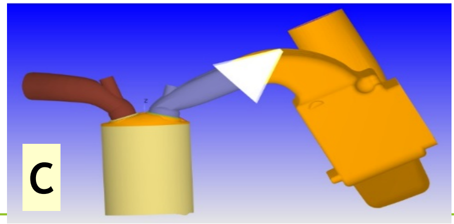
3D-CFD optimization of water injection configuration

Based on the evaporation index, configurations A and C led to almost the same effectiveness of water evaporation, which remained in both cases rather high in comparison with configuration B (injection from the bottom with perpendicular flow).









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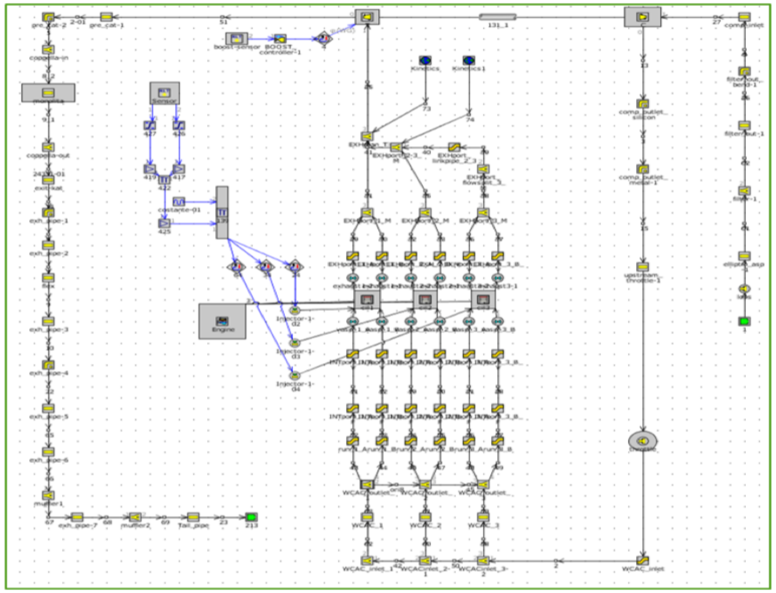
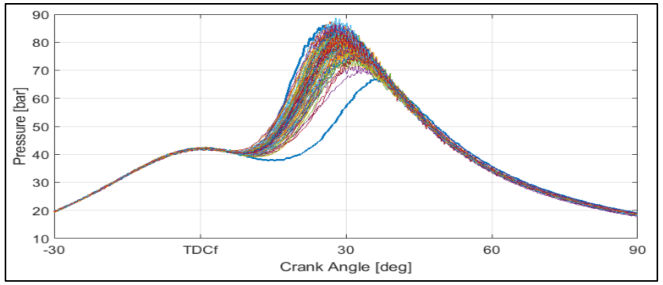
0D/1D combustion simulation and knock prediction

- Results of the experimental investigations and results obtained from 3D-CFD analysis were merged to calibrate a 0D combustion model in GT Power to simulate the effect of water injection on the combustion process and on knock mitigation.

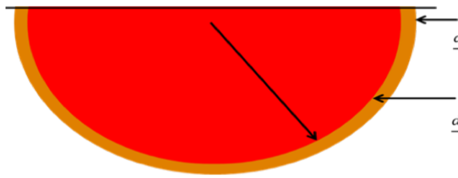
- The model is capable to reproduce Cycle to Cycle Variations (CCV) of the combustion process, and the probability of knock occurrence on a cycle by cycle basis.



GT-Power 1D/0D engine model



CCV of the combustion process



Entrainment

$$\frac{dM_e}{dt} = \rho_u A_f (S_L + S_T) \qquad S_T = C_s u' \left(1 - \frac{1}{1 + C_k (R_f/L_t)^2}\right)$$

Burn-up

$$\frac{dM_b}{dt} = \frac{M_e - M_b}{\tau} \qquad \tau = \frac{C_t \lambda}{S_L}$$

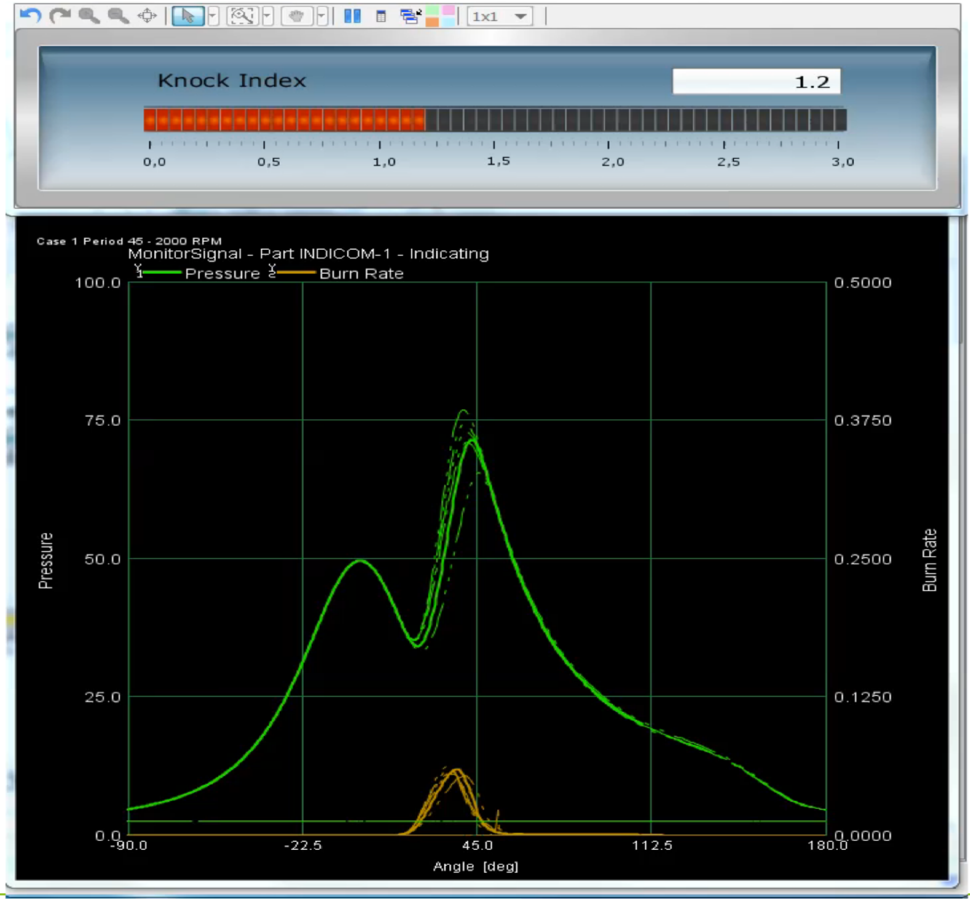
SI Turb 0D model used in GTPower

0D/1D combustion simulation and knock prediction

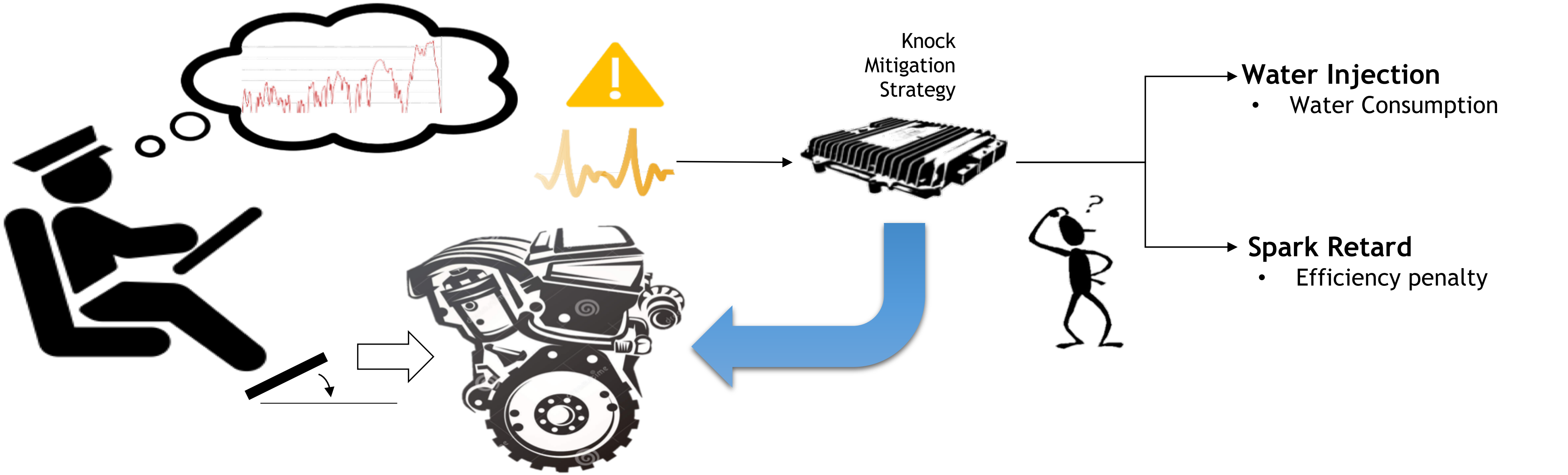
OPERATING POINT

2000 rpm@WOT

(CCV artificially emphatized)



0D/1D combustion simulation and knock prediction



SITurb

- CCV Model
- Knock Model

→

- Evaluate knock occurence probability during transients
- Mimic ECU Knock Control Strategy in GT
  - Evaluate water consumption
  - Evaluate efficiency penalty

Agenda

- Introduction
- Experimental activity
- CFD-3D model and validation
- 3D-CFD optimization of water injection configuration
- 0D/1D combustion simulation and knock prediction
- **Conclusions**

Conclusions

- From both 3D-CFD simulations and experiments it was observed that the use of only **one injector per cylinder** leads to results **similar to** the ones achieved by using **two injectors**, with a significant cost reduction.
- It has been observed that **phasing** of the water injection **has significant effect on the water evaporation and on its impact on the liner.**
- The **effect of injection pressure is negligible**, and lower injection pressure should therefore be preferred.
- It is **not worth to increase the Water to Fuel ratio above 0.5** because the incremental benefits in the combustion phasing and in BSFC become marginal.

FCA
FIAT CHRYSLER AUTOMOBILES
CRF

POLITECNICO DI TORINO
Dipartimento Energia

Analysis of Water Injection Potential for Knock Mitigation

Luciano Rolando – Politecnico di Torino

CONVERGE USER CONFERENCE – EUROPE - 2018
Savoia Hotel Regency - Bologna, Italy
March 19 – 23, 2018