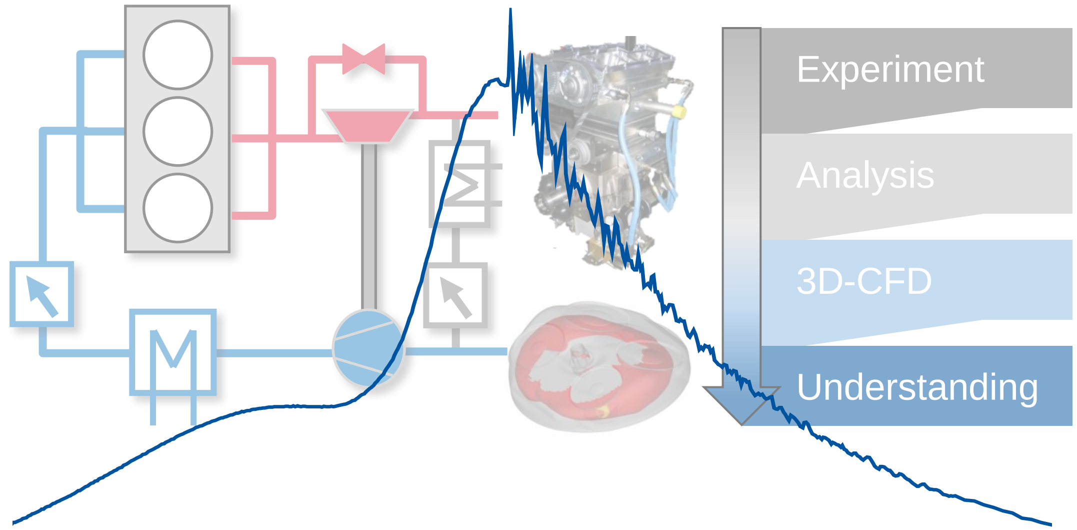
NUMERICAL STUDY OF KNOCK INHIBITION WITH COOLED EXHAUST GAS RECIRCULATION



Institute for Combustion Engines
RWTH Aachen University

Prof. Dr.-Ing. Stefan Pischinger

Bologna, March 20th, 2018

Max Mally
Dr.-Ing. Marco Günther
Prof. Dr.-Ing. Stefan Pischinger

Agenda/Content

- Introduction
- Experimental investigation
- Numerical investigation
- Summary and outlook

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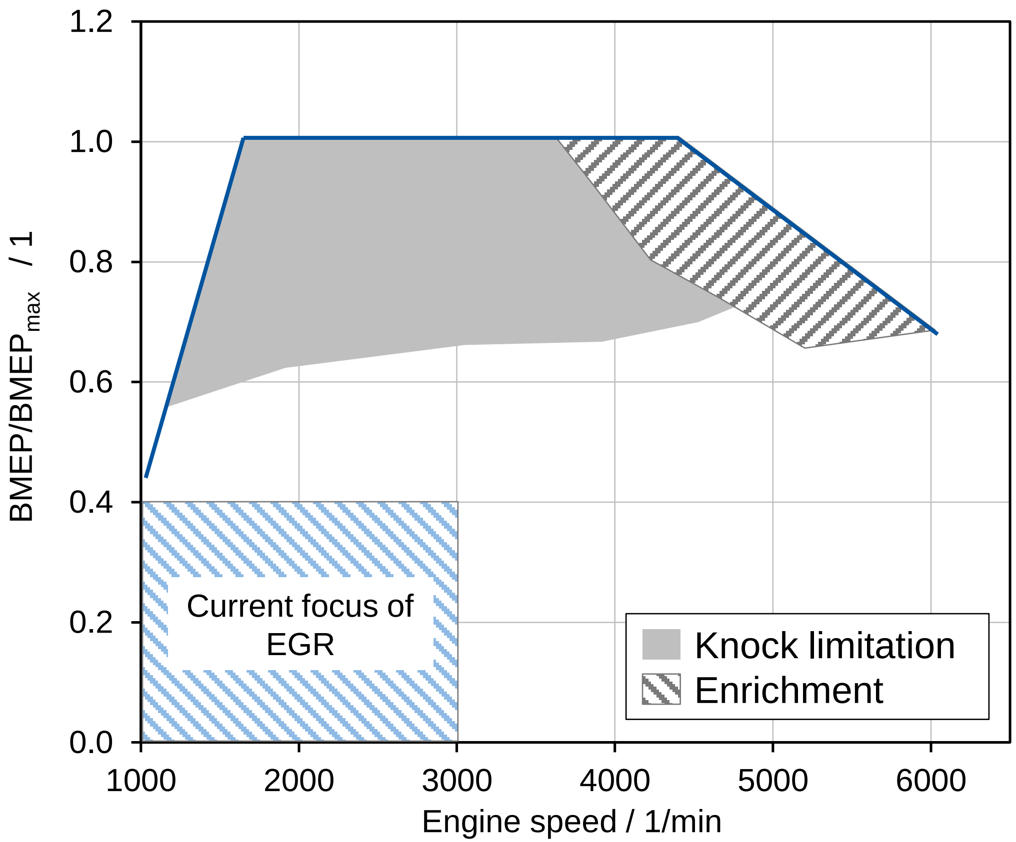
Introduction
Simulation approach for layout of full load EGR combustion system needed

REDUCED EFFICIENCY OF CONVENTIONAL GASOLINE ENGINES DUE TO KNOCK AND FULL LOAD ENRICHMENT



<u>EGR is a powerful measure to face these problems</u>

- However, development of a full load EGR combustion system is a complex task which requires reliable CAE
- 3D-CFD simulation approach needed to predict combustion and knock under the influence of EGR
  - Experimental Database
  - Definition of simulation methodology
  - Validation of numerical models

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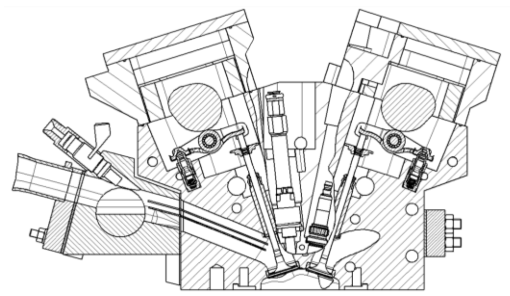
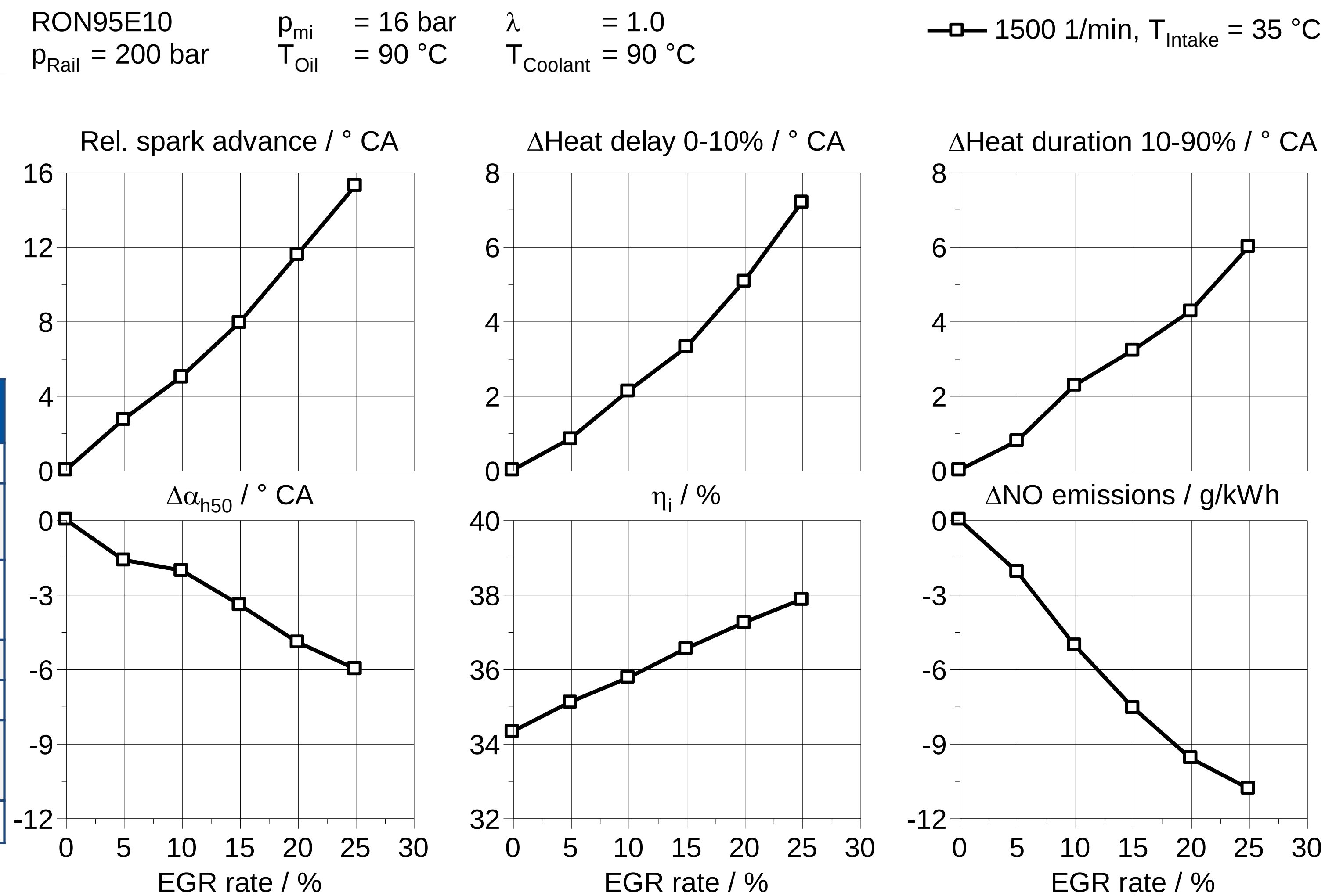
Experimental investigation
Cooled EGR is a powerful measure to inhibit knock and increase efficiency



Engine specifications		
Stroke (s)	90.5	mm
Bore (D)	75	mm
s / D	1.207	1
Engine displacement	399	cm³
Connection rod length	152	mm
Piston-pin offset (thrust side)	0.5	mm
Compression ratio	10.9	1



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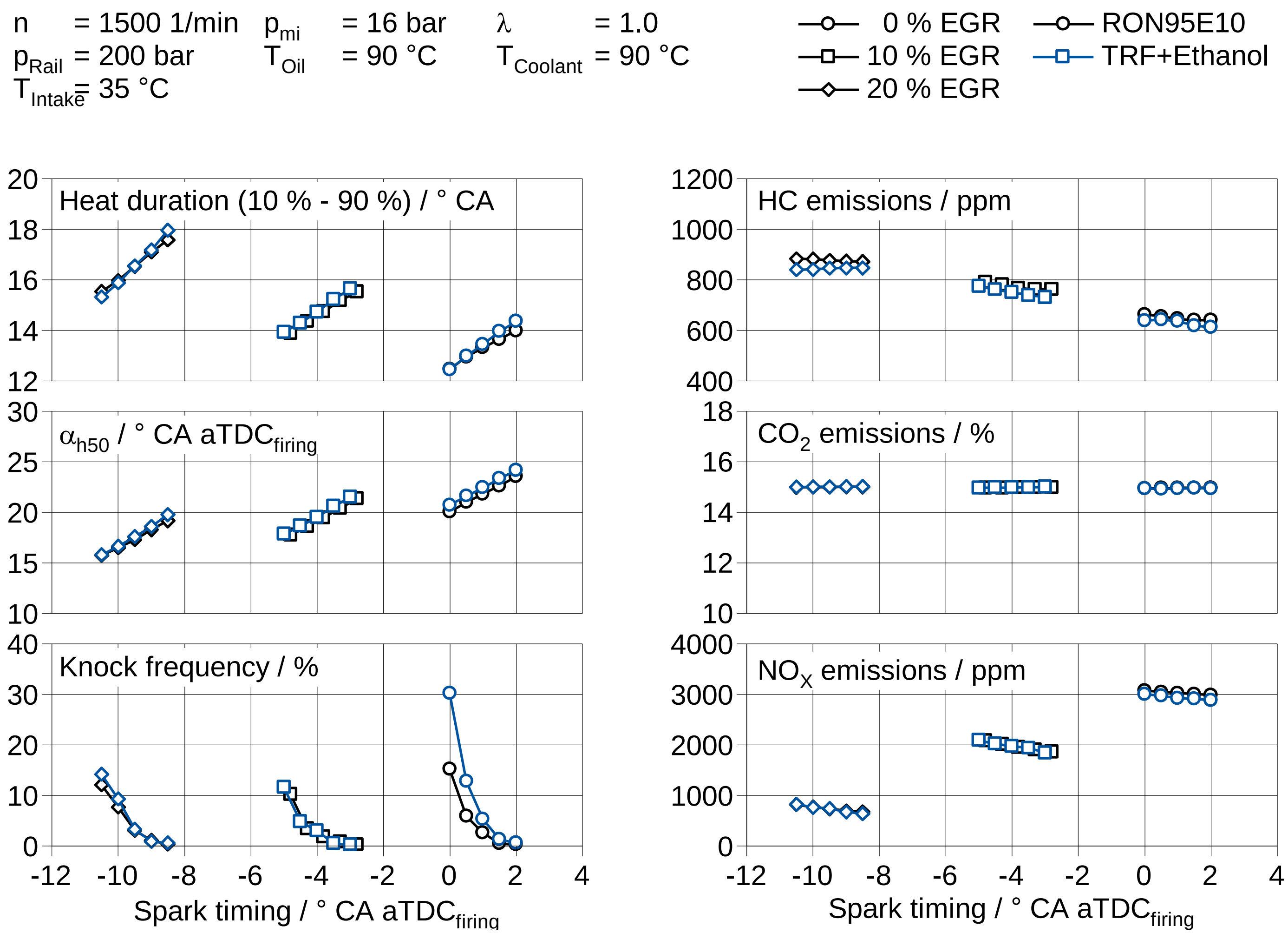
Experimental Investigation
Good agreement in terms of knocking and emissions with TRF+E surrogate

n = 1500 1/min, p_{Rail} = 200 bar, T_{Intake} = 35 °C
p_{mi} = 16 bar, T_{Oil} = 90 °C
λ = 1.0, $T_{Coolant}$ = 90 °C



	RON / -	MON / -	H/C / 1	
RON95E10	96.5	85.2	1.94	
Isooctane	100	100	2.25	
PRF95	95	95	2.25	
TRF + Ethanol	95	86.6	1.93	1)
	96.2	88.7	1.93	2)

- 1) Properties according to blending rules
- 2) Measured properties from CFR engine
- Validated kinetic mechanism available from ITV

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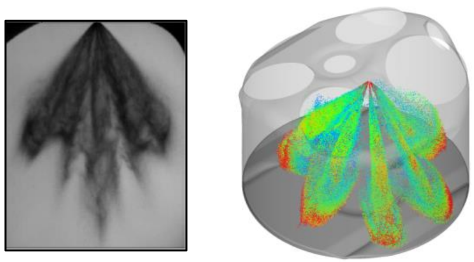
Numerical investigation
Numerical setup for simulation of mixture formation

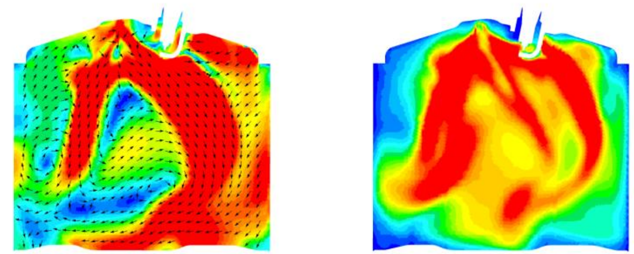
Mixture Formation | Combustion

270° CA | 660° CA | 800° CA

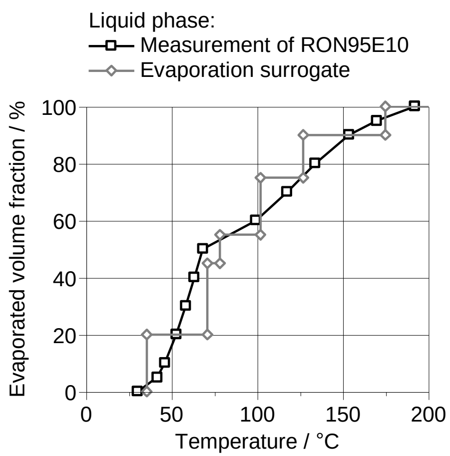
- Calibrated KH-RT model / Kuhnke Wall film model

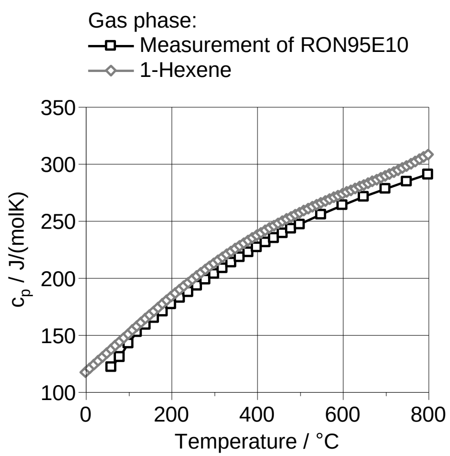


- Standard k-ε turbulence model

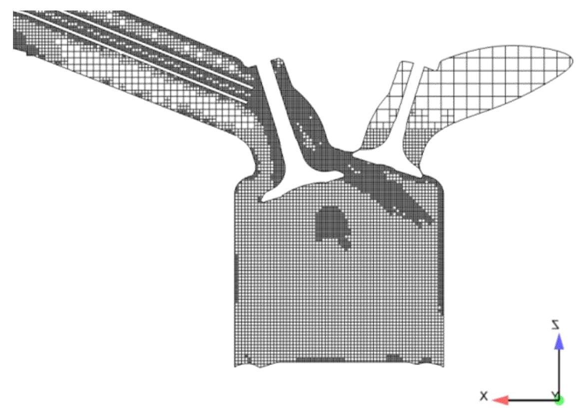


- Dedicated surrogate for liquid phase





- Velocity AMR and Embedding (0.5 mm cells)



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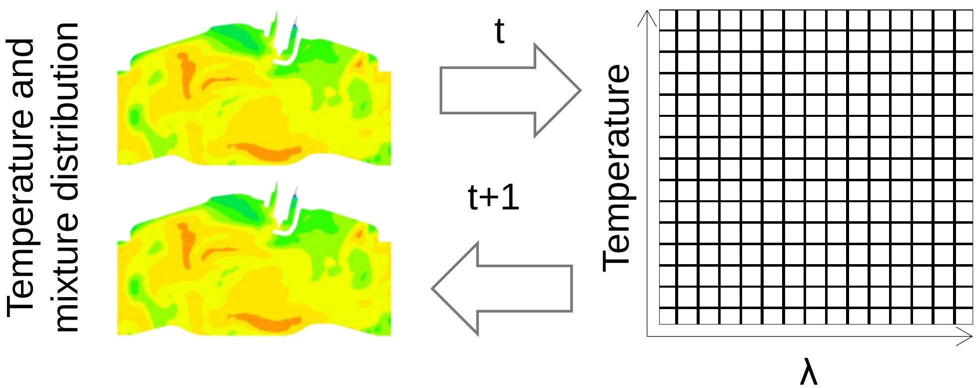
Numerical investigation
Numerical setup for simulation of combustion and knock

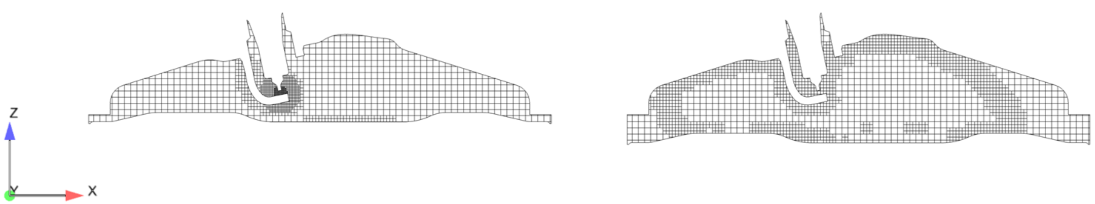
Mixture Formation → Combustion

270° CA | 660° CA | 800° CA

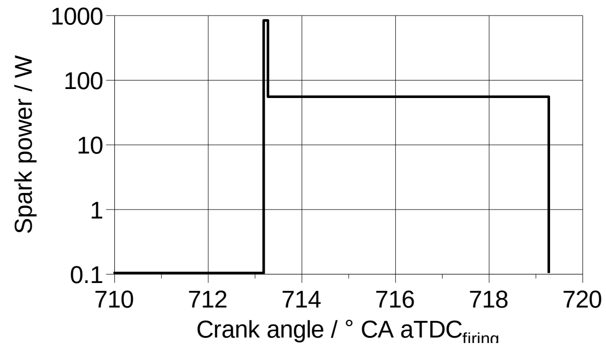
- SAGE Chemistry Solver and Multi-Zone approach

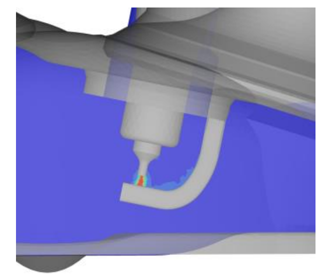


- Spark embedding (0.0125 mm) and Temperature AMR (0.5 mm)

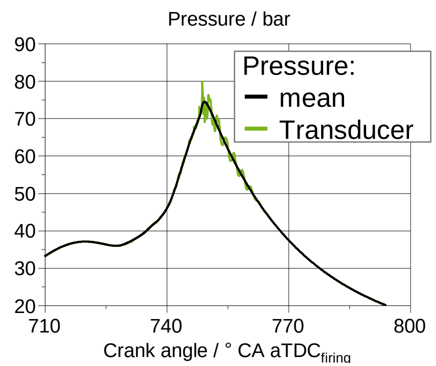


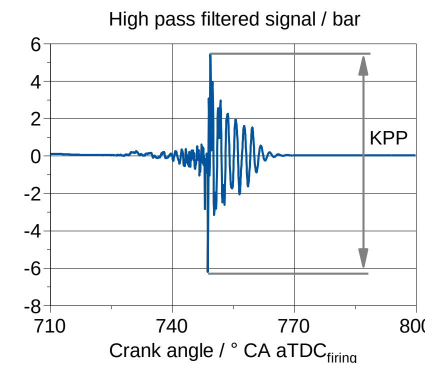
- Spark model (Energy line source)





- Quantitative knock evaluation at transducer location





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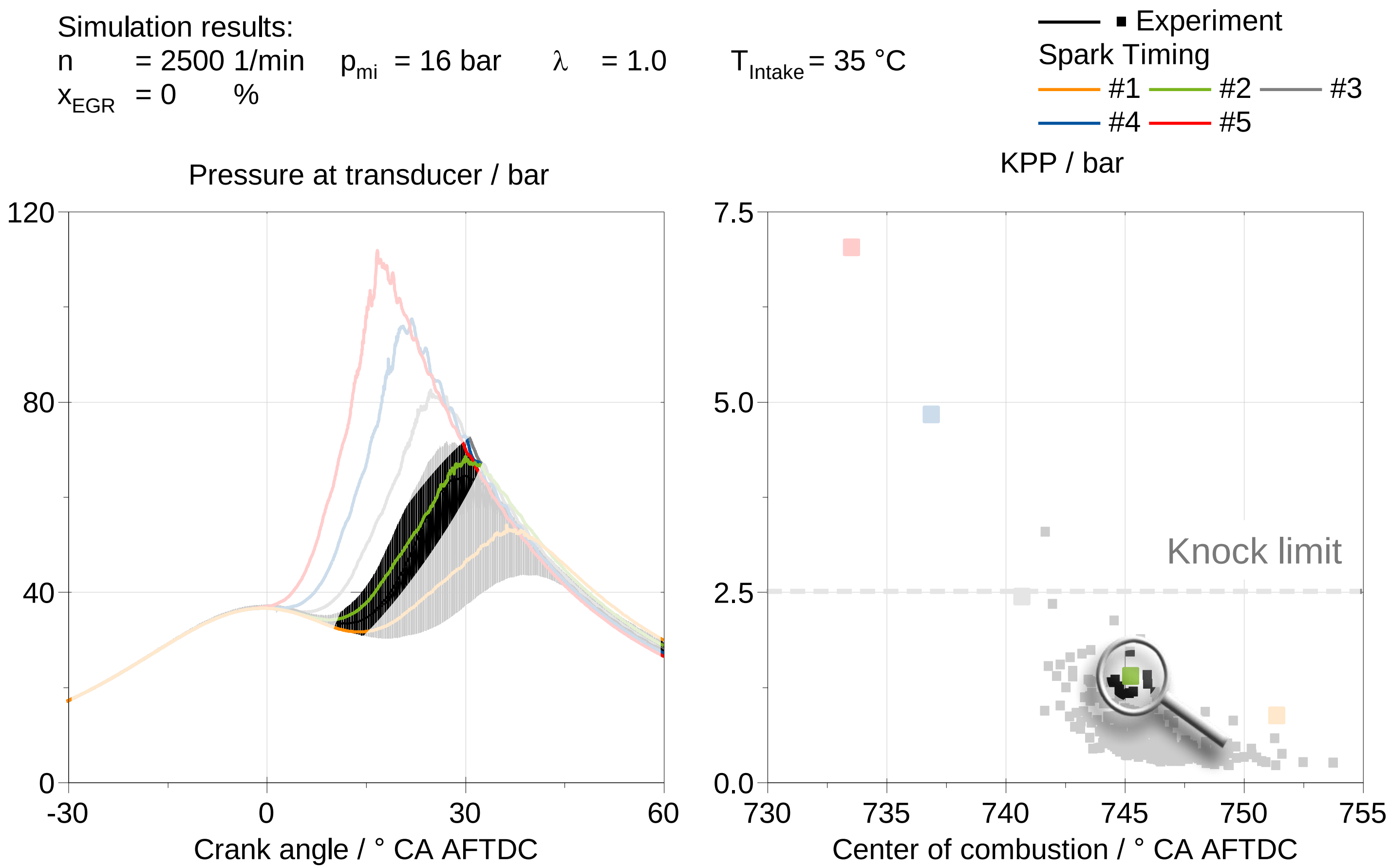
Numerical investigation
Simulation results are feasible and confirm test bench knock limitation

SIMULATION RESULTS OF 2500 1/MIN, 0% EGR, T_{INTAKE} = 35 °C

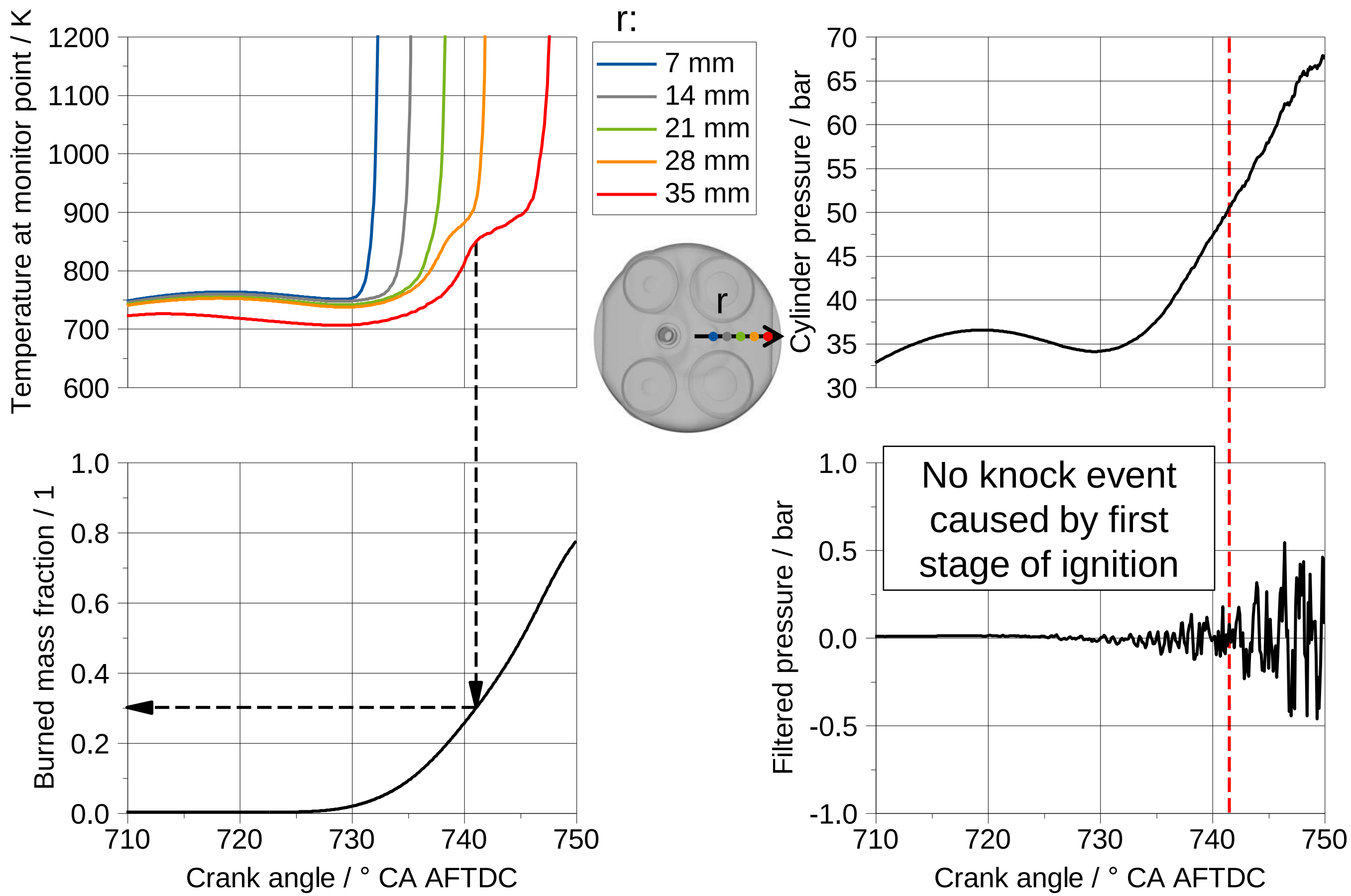
- During testing cycle to cycle variations are observed
- Fluctuations in combustion cannot be resolved with a RANS* approach
- Different combustion phasing in CFD is achieved via a virtual spark timing sweep
- Combustion and knock limitation successfully reproduced with simulation approach

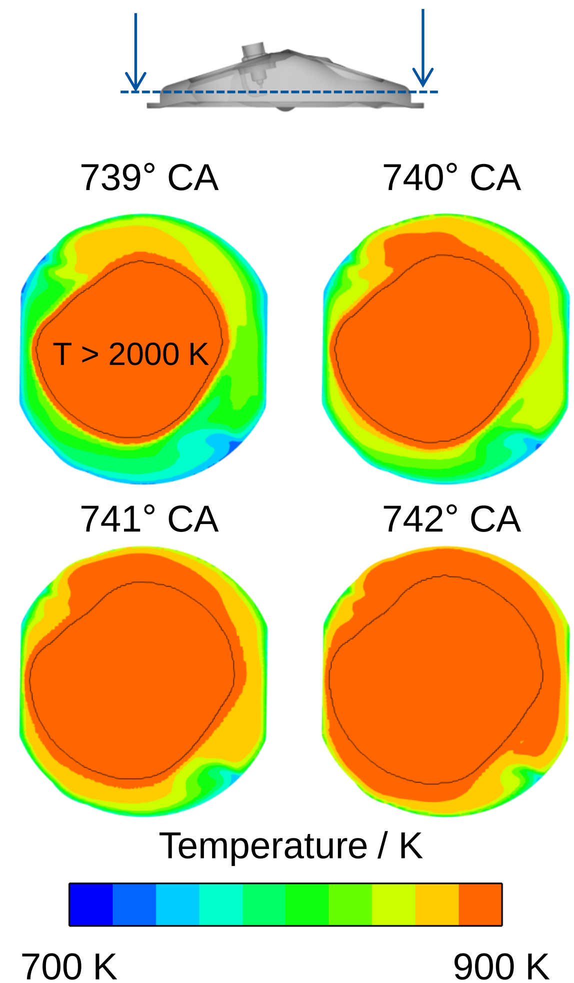


*: Reynolds-Averaged Navier-Stokes

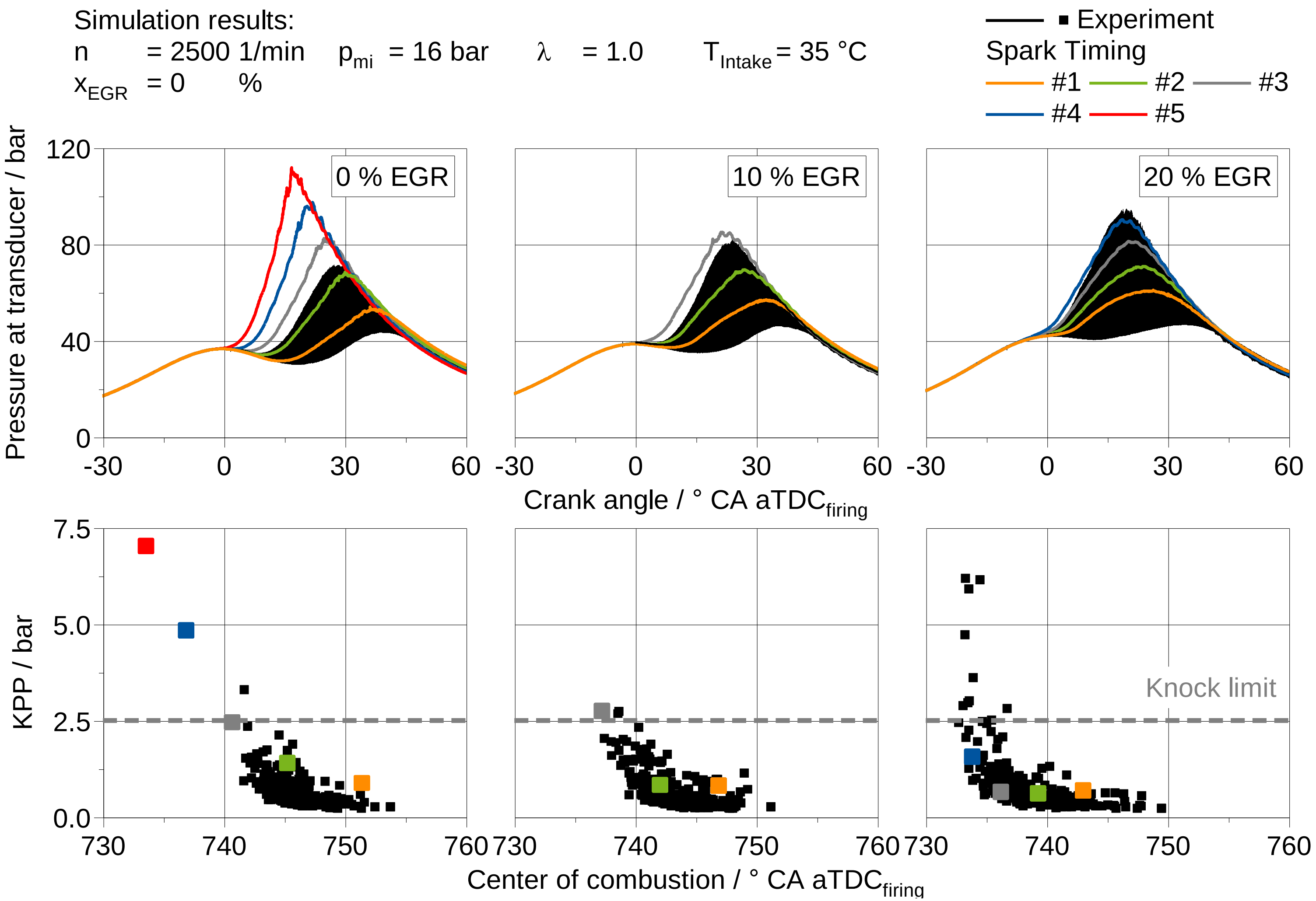
Numerical investigation
First stage ignition observed early during combustion

SIMULATION RESULTS OF 2500 1/MIN, 0 % EGR, T_{INTAKE} = 35 °C





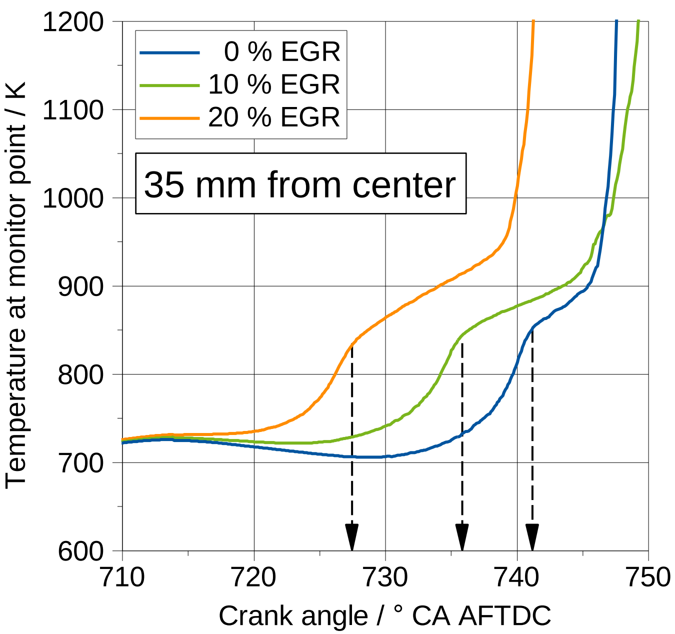
Numerical investigation
Effect of EGR on combustion is well captured by modelling approach

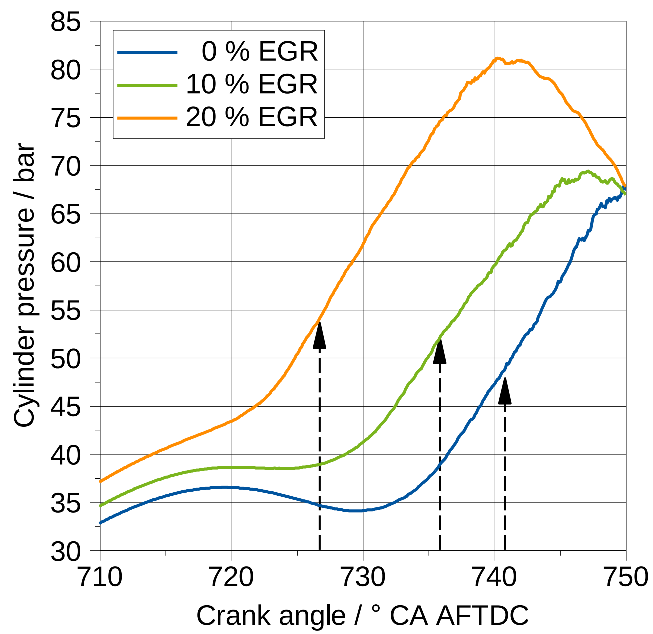


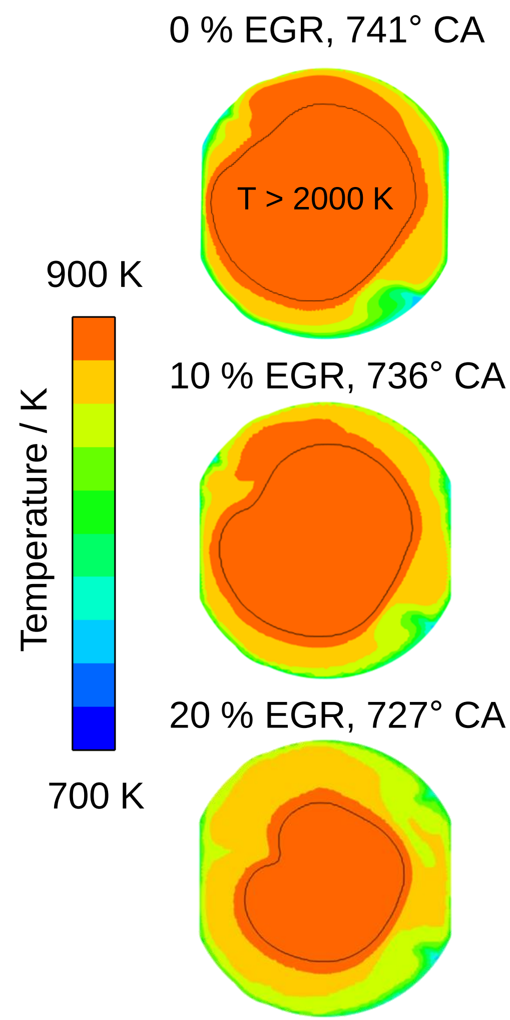
- Knock limit well captured at 0 and 10 % EGR
- At 20 % the knocking tendency is underestimated by the simulation model
- The high cycle to cycle variation makes it difficult to capture the knock limit with a RANS approach

Numerical investigation
First stage ignition observed earlier when EGR is added

SIMULATION RESULTS OF 2500 1/MIN, 0-20 % EGR, T_{INTAKE} = 35 °C







- Despite similar temperature level the first stage of ignition is occurring earlier in the combustion simulation if EGR is added
- The cylinder pressure where first stage ignition is occurring is increasing with EGR

Numerical investigation
Simulation results are feasible and confirm test bench knock limitation

SIMULATION RESULTS OF 2500 1/MIN, 0% EGR, T_{INTAKE} = 35 °C

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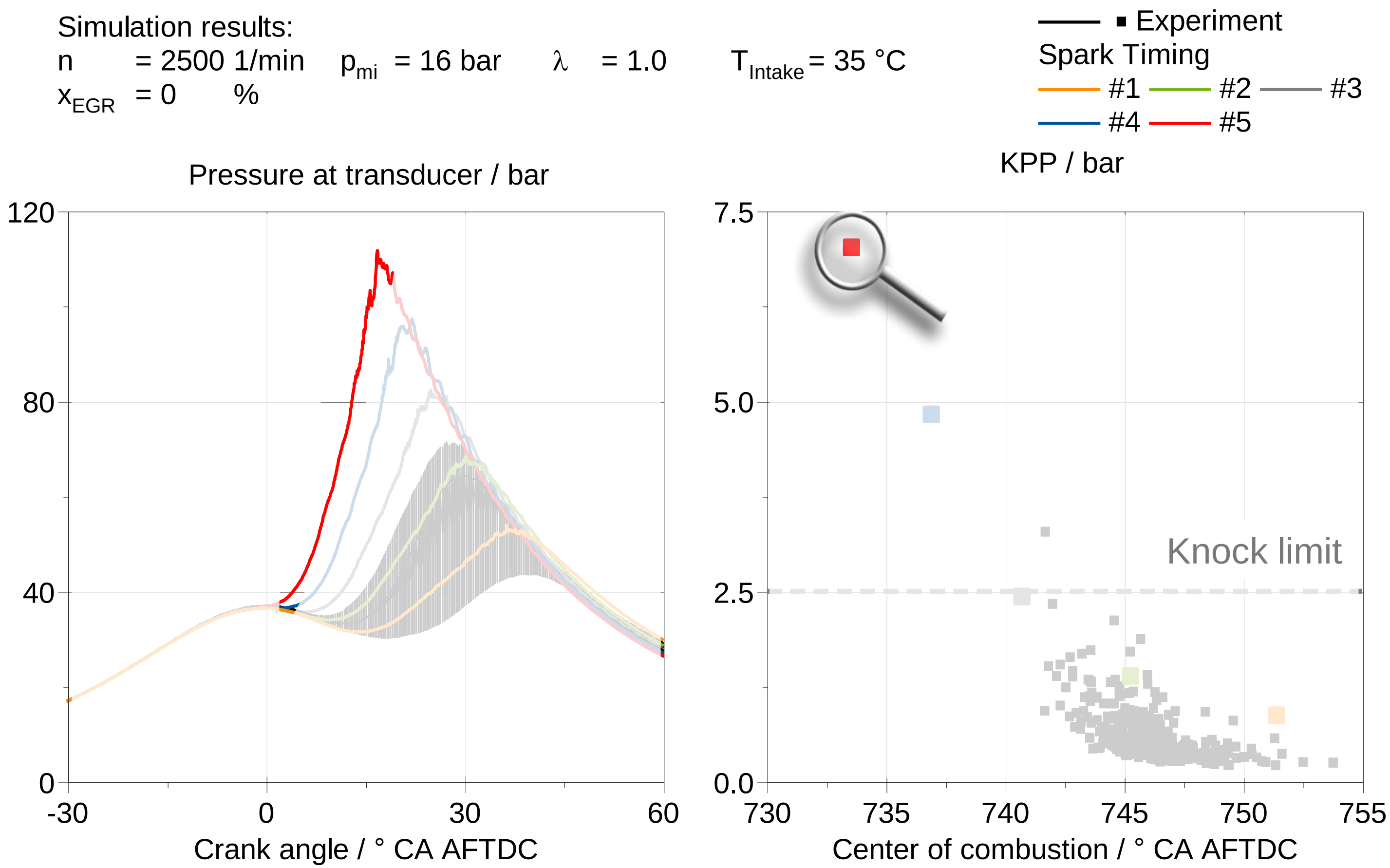
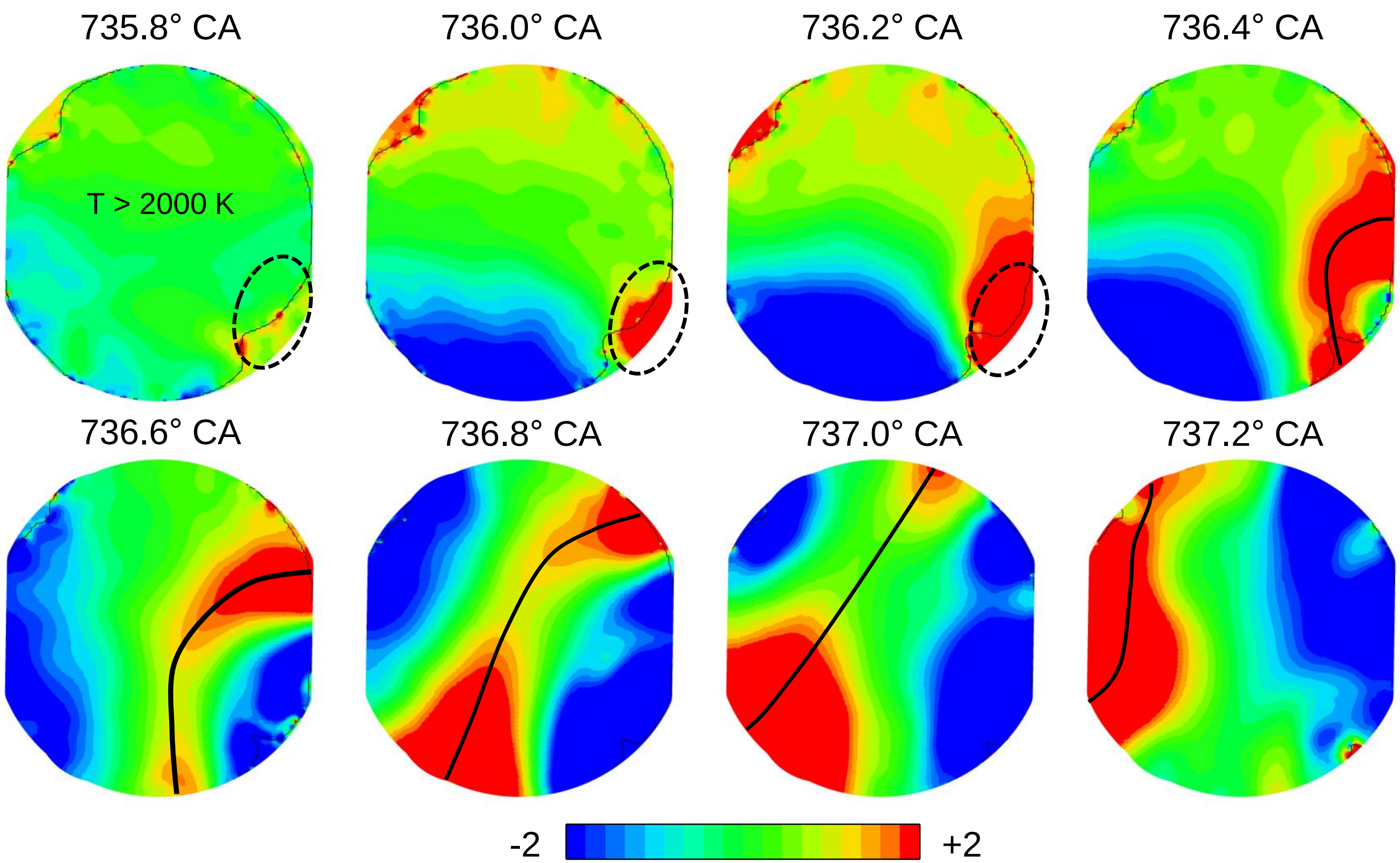


*: Reynolds-Averaged Navier-Stokes

Numerical investigation
Severe knock caused by auto-ignition ahead of the flame front

PRESSURE WAVES ARE FORMED IN CASE OF FAST FLAME PROPAGATION (DETONATION)

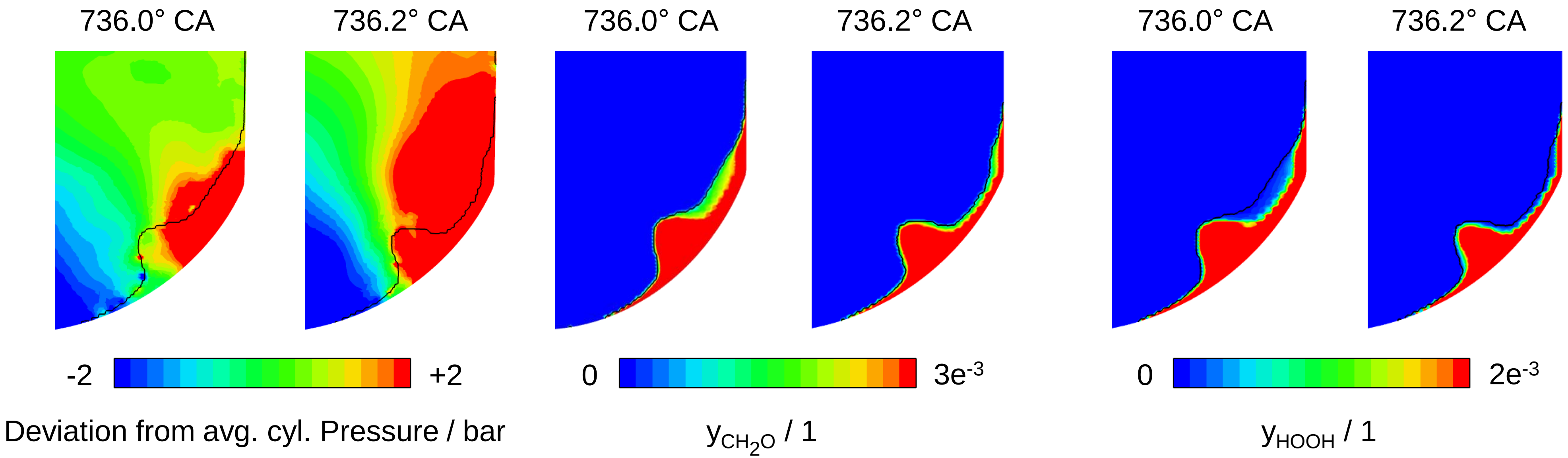


Deviation from avg. cyl. Pressure / bar

- In case of a severe knock event an extreme fast flame propagation is observed
- This is in-line with the detonation theory
- Due to the high heat release the local pressure cannot balance out with the surrounding environment
- The formed pressure waves travels through the combustion chamber and is reflected at the opposite wall

Numerical investigation
Formation of OH radicals by dissociation of HOOH leads to knock

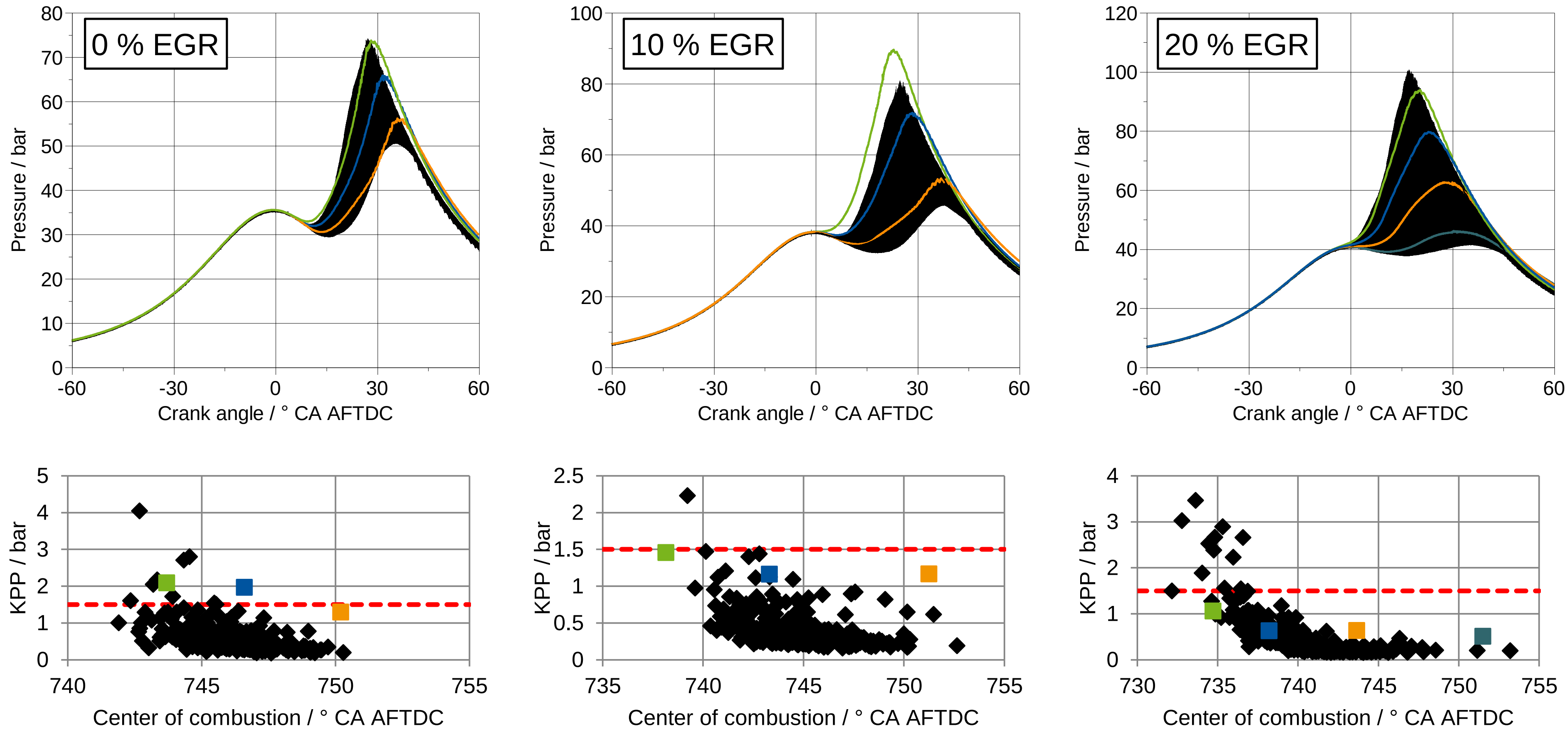
AS CH_2O AND HOOH ARE CONSUMED AHEAD OF THE FLAME FRONT A PRESSURE WAVE IS FORMED



- At high temperatures hydrogen peroxide reacts to two OH-radicals which significantly increase overall reaction velocity
- In this process the high temperature ignition reactions are triggered and CH_2O is consumed

Numerical investigation
Good Match of Combustion and Knock with EGR at 1500 1/min as well

SIMULATION RESULTS OF 1500 1/MIN, 0-20 % EGR, T_{INTAKE} = 35 °C



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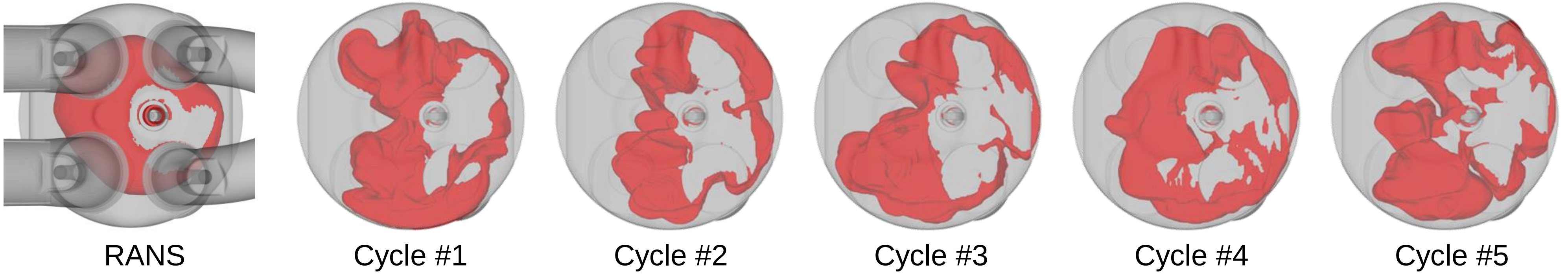
Summary
Good performance of RANS simulation methodology

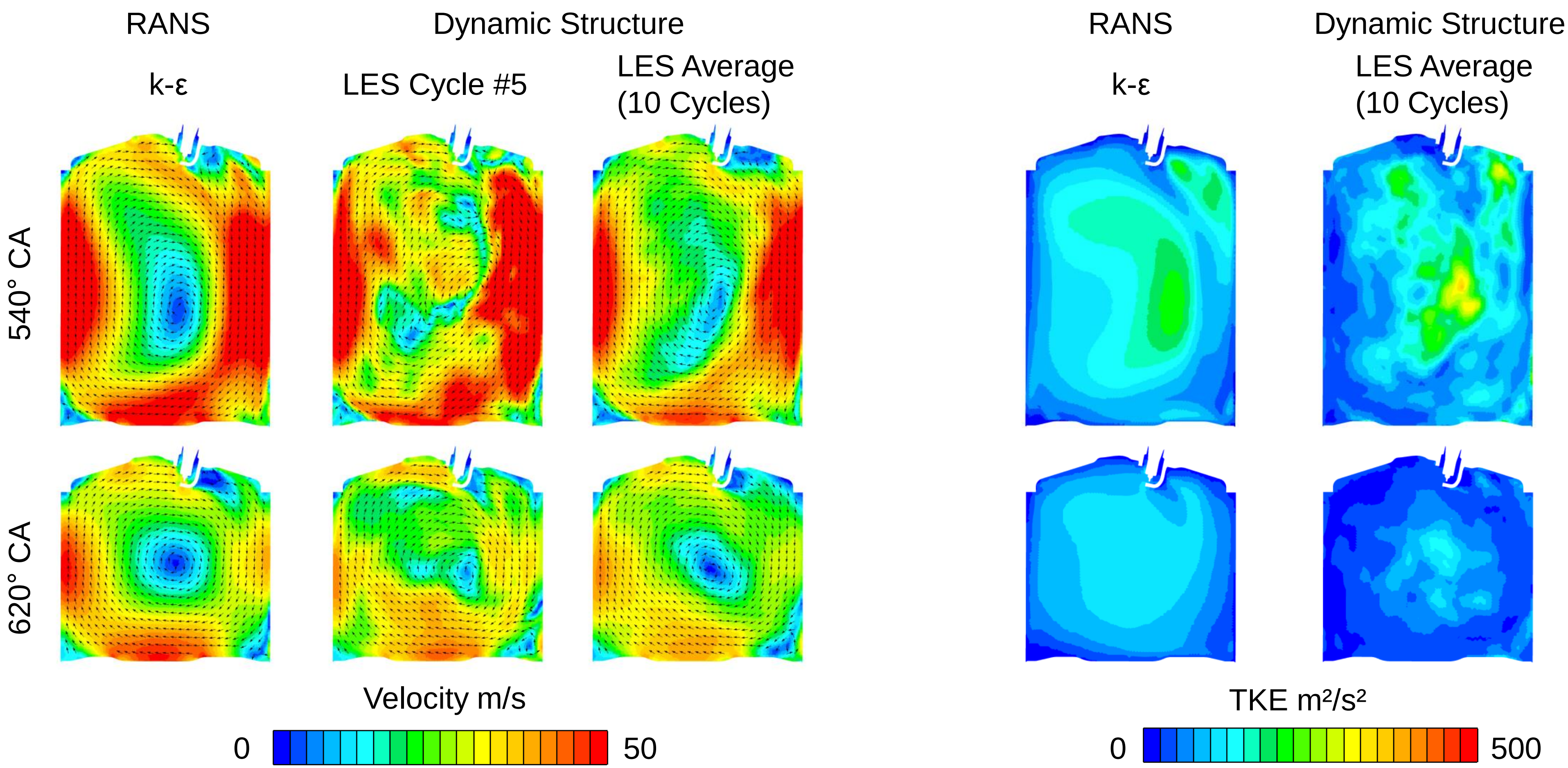
KEY FINDINGS OF NUMERICAL INVESTIGATION

- A RANS simulation model with coupled reaction mechanism and a validated gasoline surrogate was build up
- Simulation methodology was able to successfully calculate the combustion under the influence of EGR and changing turbulence
- Although cycle-to-cycle variation cannot be resolved with a RANS approach the knock limit could well reproduced with spark timing sweeps in the simulation model at most operating points
- First stage ignition is playing an important role in the unburned zone and is affecting the temperature history of the unburned gas
- This is especially true for combustion with EGR since the time of first stage ignition is only slightly affected by EGR
- Possible improvement of methodology with large eddy simulation?



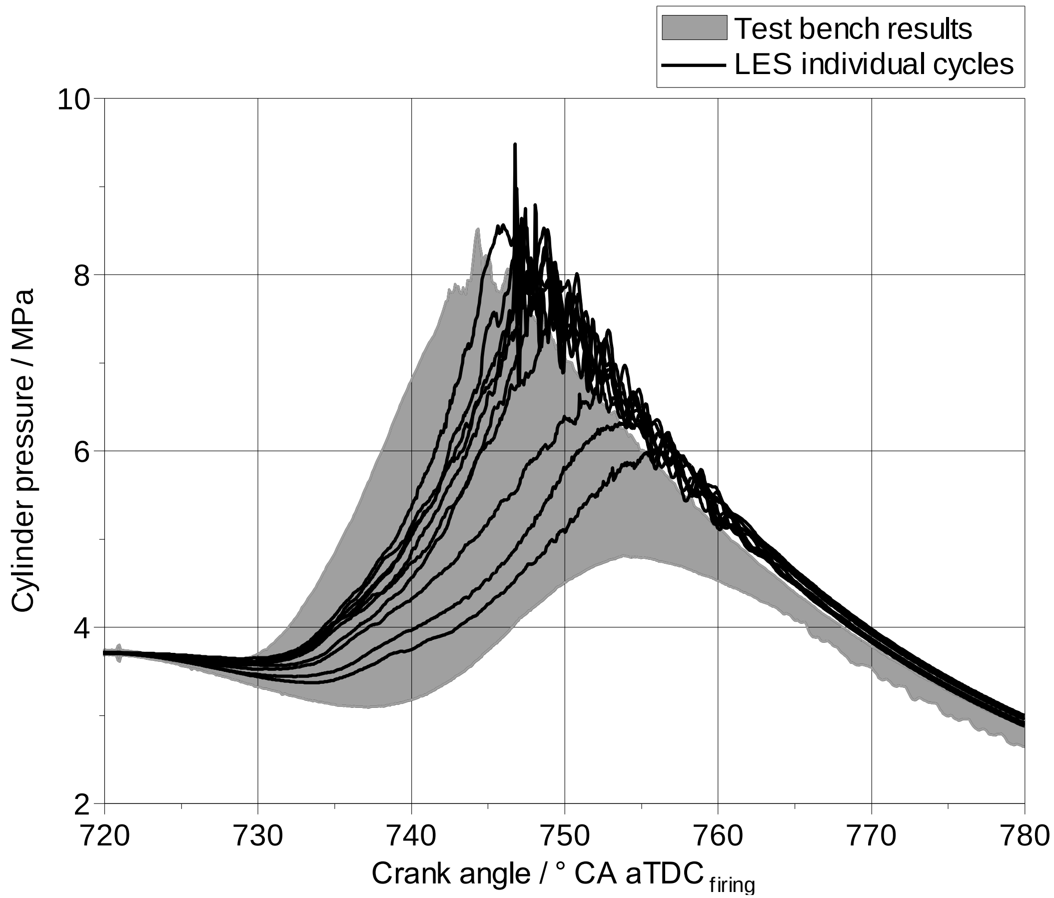
Outlook
Large eddy simulation of ten individual cycles with dynamic structure model

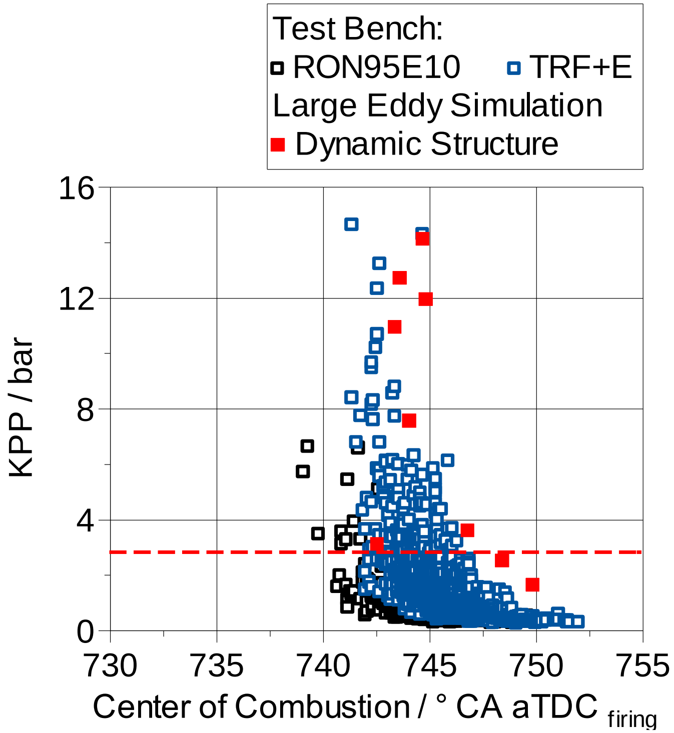
SIMULATION RESULTS OF 2500 1/MIN AND 0 % EGR: FAIR MATCH OF FLOW FIELD AND TKE ON AVERAGE



Outlook
Good match of fluctuation in combustion

HIGHER KNOCK TENDENCY OF SURROGATE AT THIS POINT IS REFLECTED IN THE SIMULATION MODEL





LES yields promising results for future investigations

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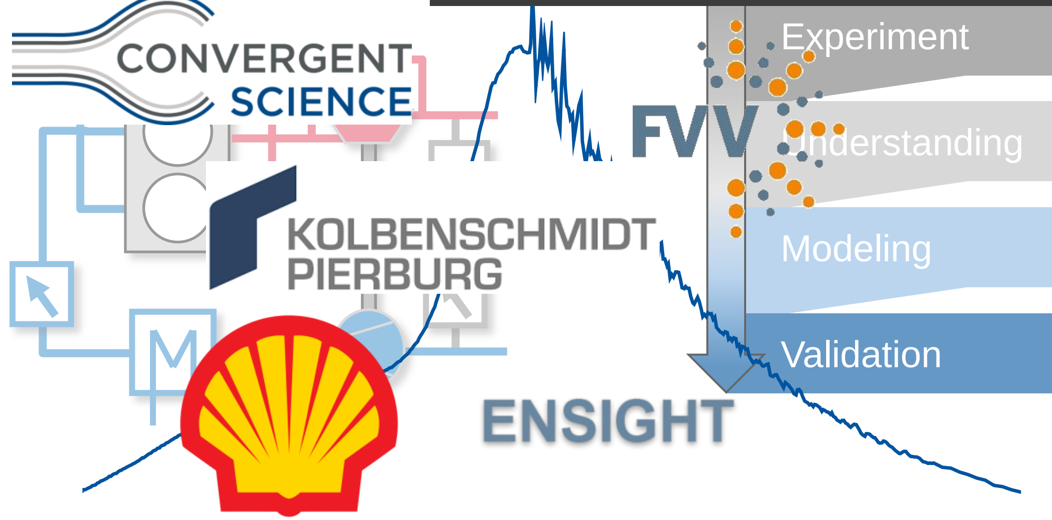
Furthermore we give special thanks to Convergent Science Inc., Shell, Kolbenschmidt-Pierburg and EnSight

THANK YOU

FOR YOUR KIND ATTENTION!

WE WOULD LIKE TO THANK:



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