Fourth Two-Day Meeting on IC engine Simulations using the OpenFOAM technology

A numerical and experimental investigation of bi-fuel RCCI combustion and TCRCI, a temperature controlled single fuel compression ignition combustion

L. Marmorini,
Marmotors s.r.l
T. Lucchini
Department of Energy, Politecnico di Milano

Summary

- Background on Temperature Controlled Reactivity Compression Ignition :
  - A Low Temperature Combustion system that has the potential of high efficiency and low soot and NO_x emissions
  - A very interesting combustion system to compete at LeMans in LMP1 class

- Experimental and numerical activity in the period 2016-2019
  - Engine modifications and test cell layout
  - Preliminary CFD analysis on combustion
  - Test program and data analysis at Dec. 2019

- Numerical simulation of RCCI and TCRCI in OpenFOAM® and first correlation with experimental analysis

Acknowledgments

A particular mention for the preparation of the paper and for the activity performed:

From Politecnico di Milano – ICE Group

Qiyan Zhou PhD Student
Filippo Gazzola MS Student

From Marmotors s.r.l.

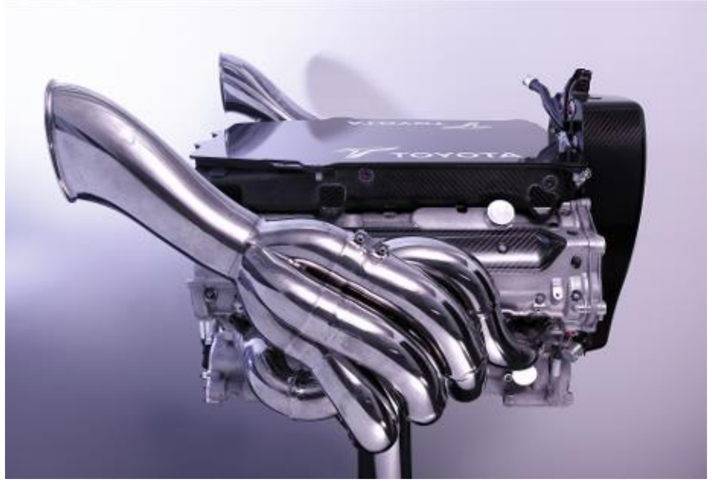
Marco Buttitta
Paolo Cotellessa
Simone Marmorini

My background: motorsport, <u>just motorsport</u>.

IC engine in F1:

- From 1990 to 2013: Naturally Aspirated engine V12, V10, V8 with no interest on BSFC but with very high efficiency (about 35%)7

- From 2014 on: Very efficient electrified power-trains (about 50%)



2010 F1 engine:

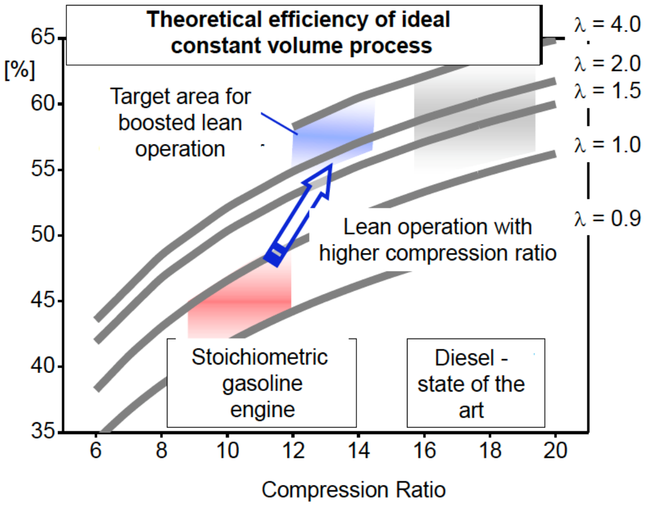
• Lean Running NA engine with Kinetic Energy Recovery System (60kW – 400 kJ per lap - no refuelling during racing) - BSFC 235 g/kW

2014 Fuel flow controlled Turbocharged Engine with ERS:

• Electric boost through MGUK (120kW-4MJ per lap and energy recovery from electrically assisted turbo-charger MGUH (no limitation) - BSFC 182 g/kW

Efficiency increase in SI engines

Compression ratio increase



Spark-assisted combustion

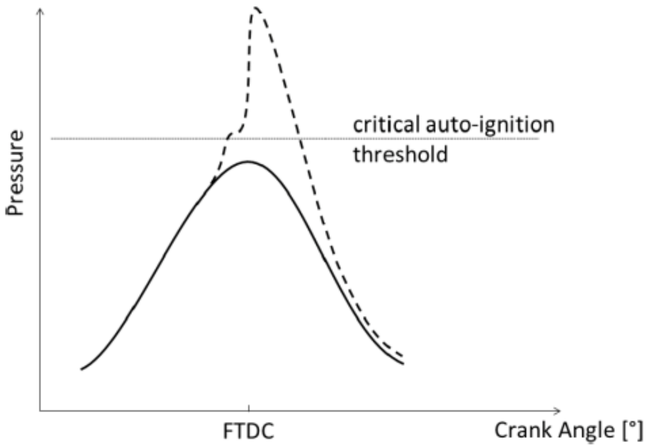


Figure 1. Schematic visualization of the auto-ignition potential.

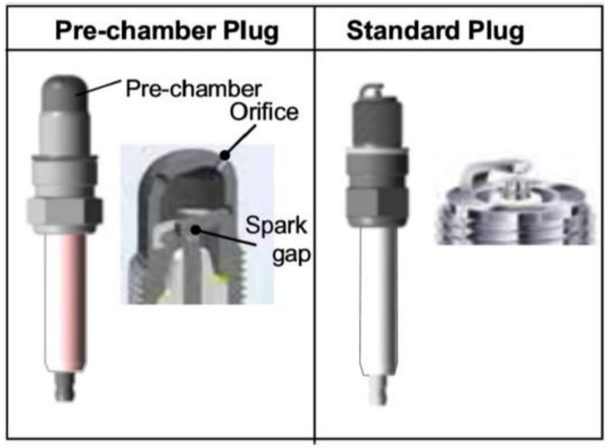
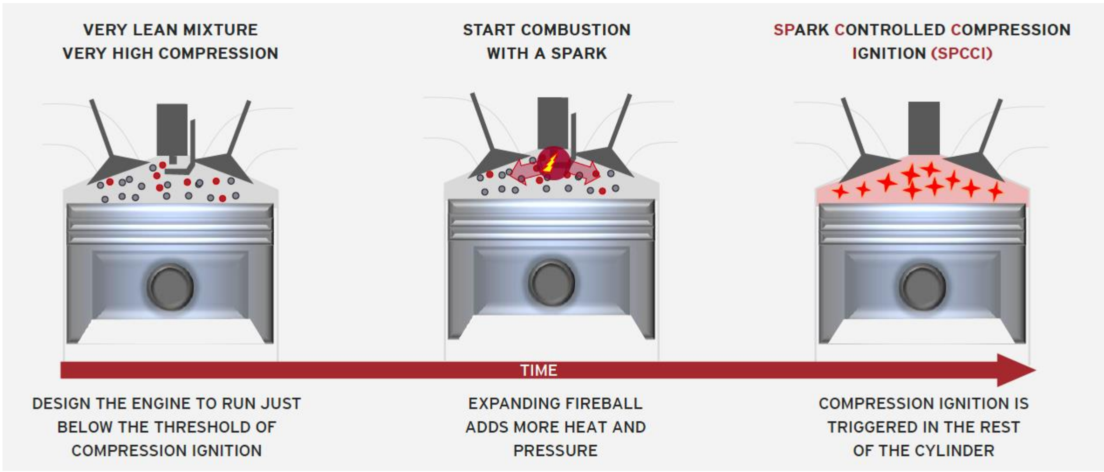
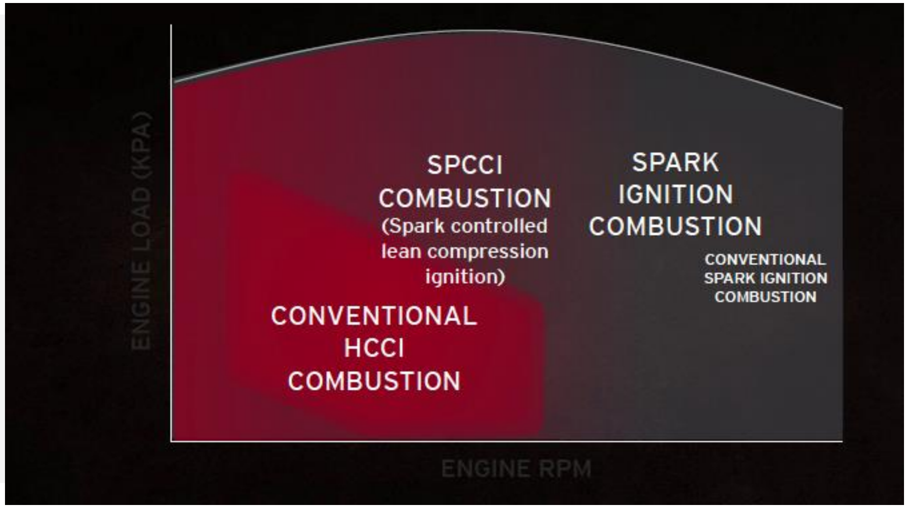


Figure 2. Pre-chamber spark plug for a gas engine [12]

Mazda Skyactive-X concept (SPCCI combustion)





Efficiency increase and emission control

High-efficiency

+

Low-emissions

CI engines → development

Use of alternative fuels

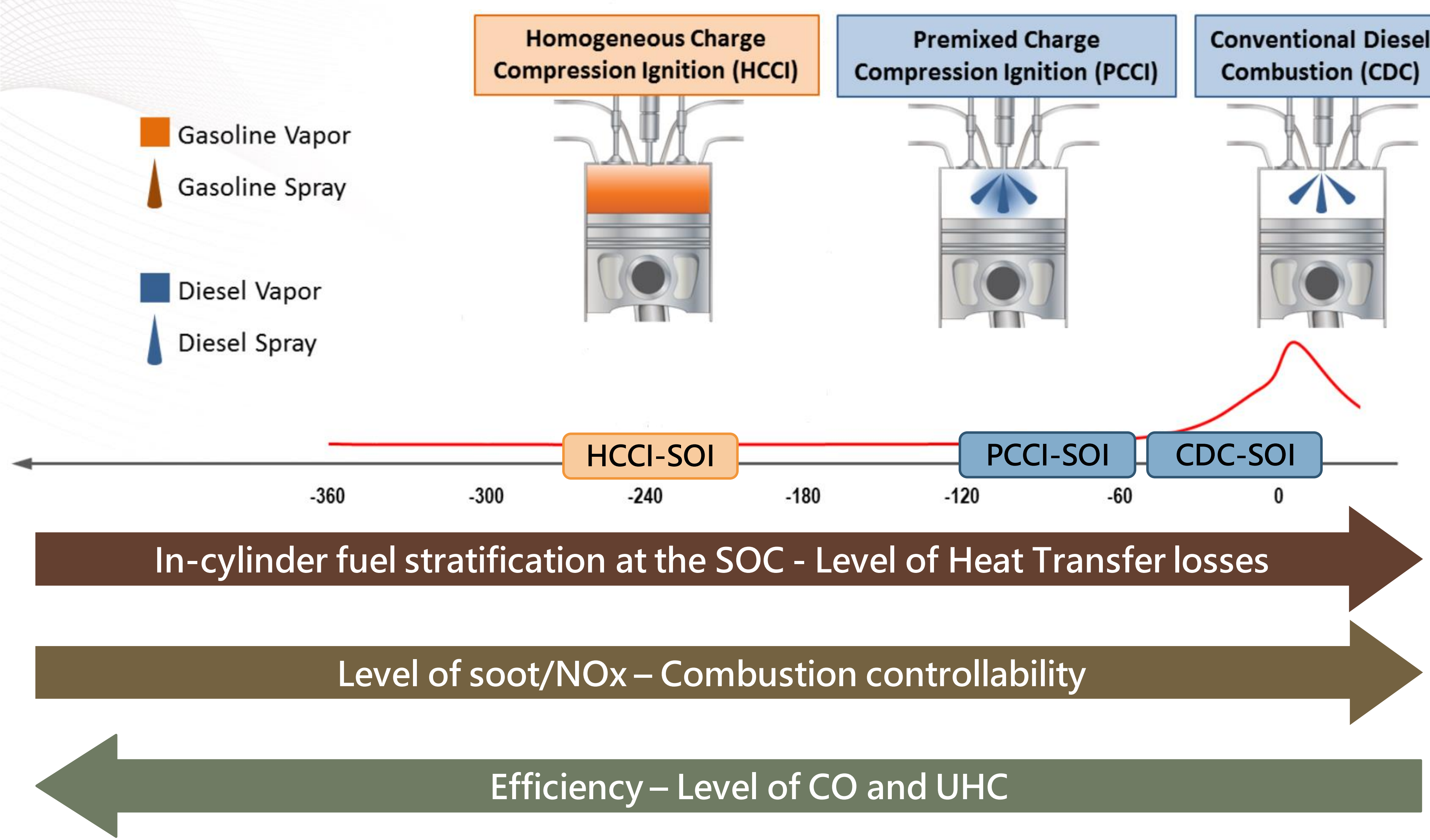
biogas, methanol, biodiesel, CNG gas, DME

After-treatment systems

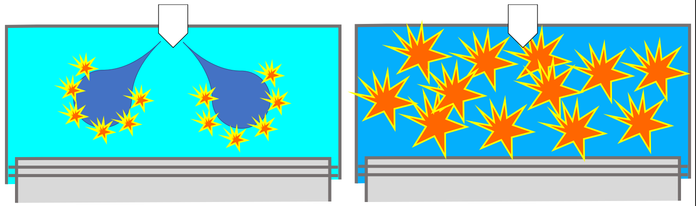
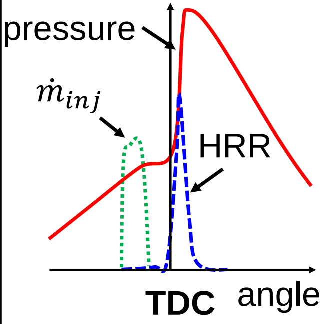
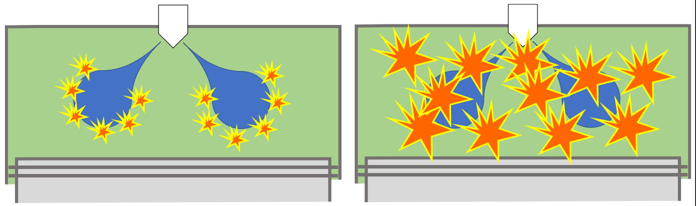
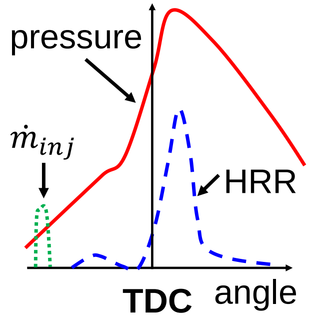
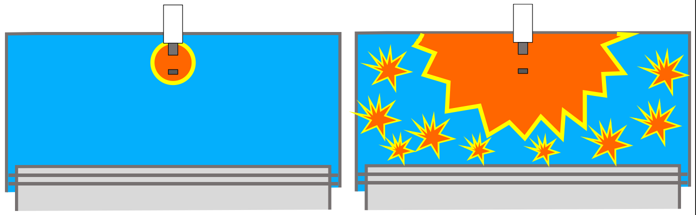
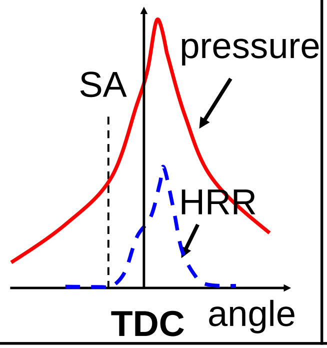
SCR, DPF, TWCC ecc.

Advanced Low-Temperature Combustion modes + **Combustion control strategies**

Advanced low-temperature combustion modes



Advanced combustion modes for direct-injection engines

PCCI	**Direct**	**Diesel, biodiesel**			~50%	HC and CO	YES
RCCI	**Direct and PFI**	**Fuel 1: Diesel Fuel 2: Gasoline, CNG, ethanol**			~55%	HC and CO	YES
SACI	**Direct or PFI**	**Gasoline, CNG, ethanol**			~50%	HC and CO	YES

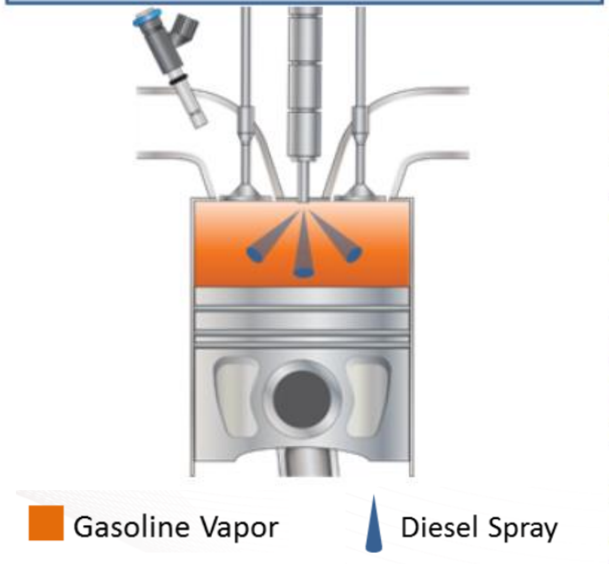
RCCI Combustion concept

Advantages:

- Higher efficiency (55-60%)
- Reduced Heat Transfer losses
- Improved combustion controllability
- Near-zero NOx and soot emissions
- Lower peak temperature

Fuel chemical kinetics control

Reactivity Controlled Compression Ignition (RCCI)



Disadvantages:

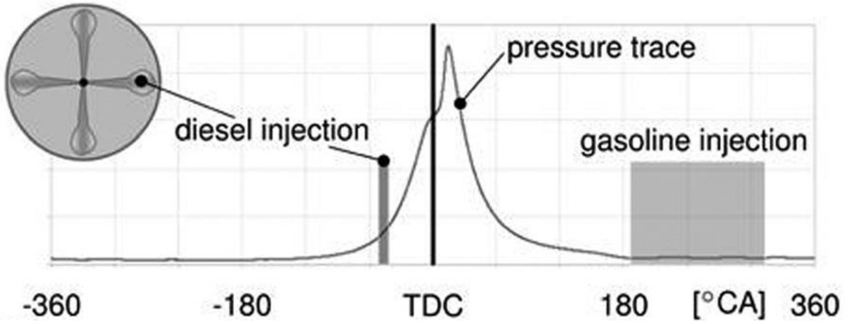
- High-perfomance turbo-machinery
- Optimization of combustion control strategies for different loads

Control parameters

Single-fuel

or

Dual-fuel



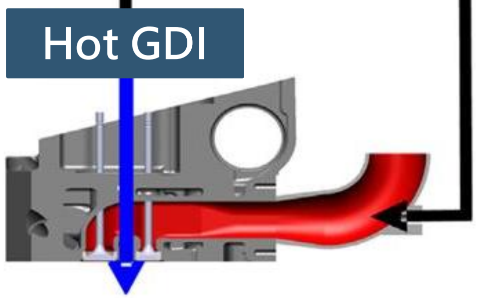
Fuel blending strategies

TCRCI Combustion concept

RCCI strategy

Single-fuel

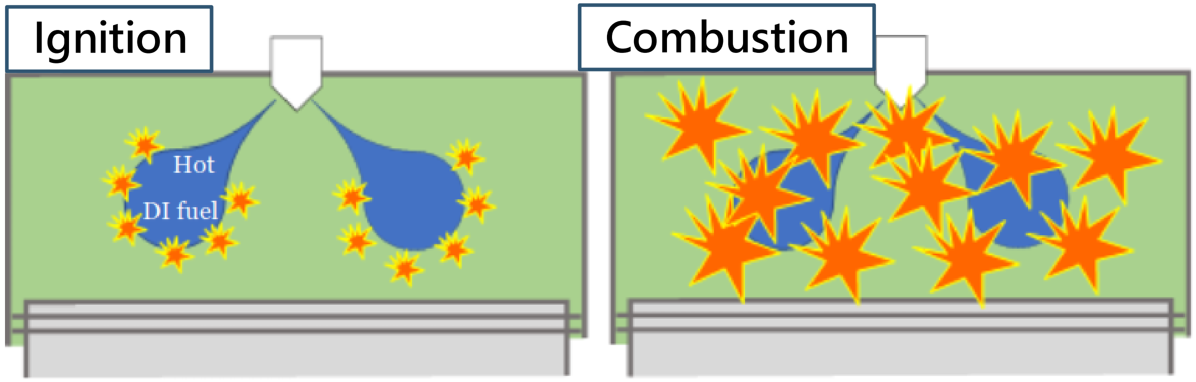
Gasoline



Heated fuel injection

Control parameter:
DI Fuel Temperature

TCRCI



Advantages:

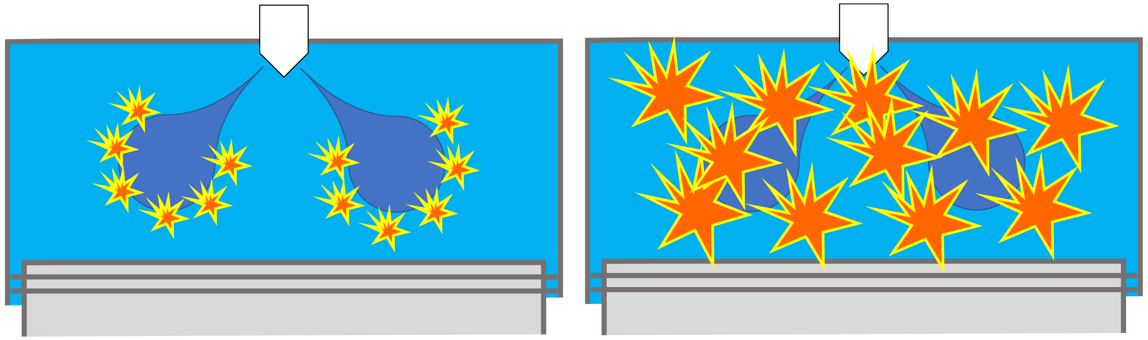
- Simple fuelling system
- Lower injection pressure
- Better mixing control
- Better reactivity stratification
- Lower pollutant emissions (HC and CO)

Disadvantages:

- High energy consumption of the DI heating system
- Lower response
- Challenging injection process

CFD

TCRCI Combustion concept



The combustion is a compression ignition of an extremely lean mixture that is triggered by a small injection of heated fuel.

Two series of injections of the same fuel at two different injection temperatures. Cold Injection and Hot Injection.

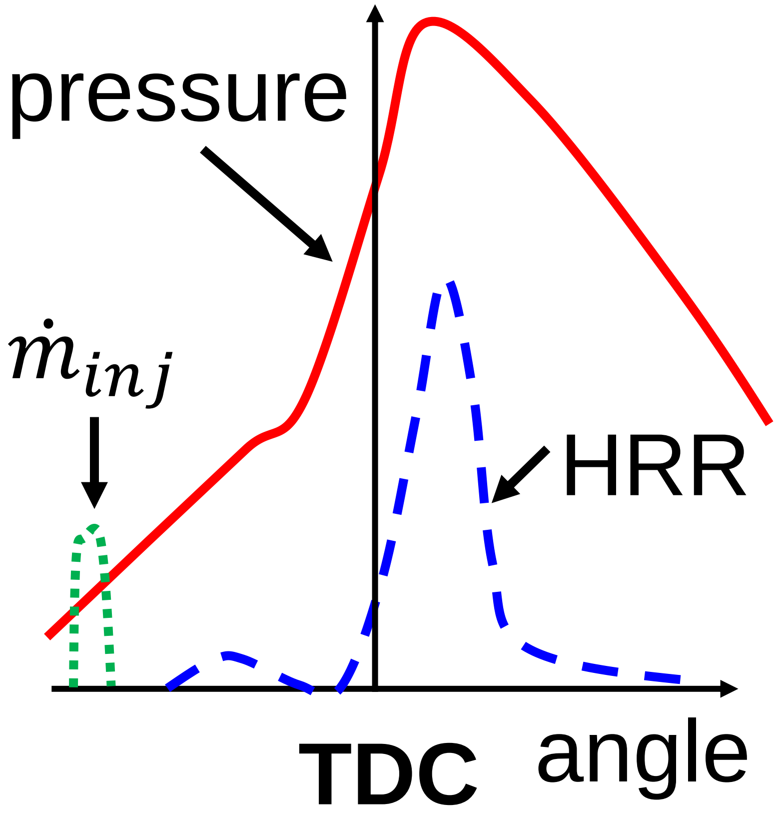
The injection system is designed for **heating of only a small percentage of the injected fuel**.

- reduced EGR and pumping losses.

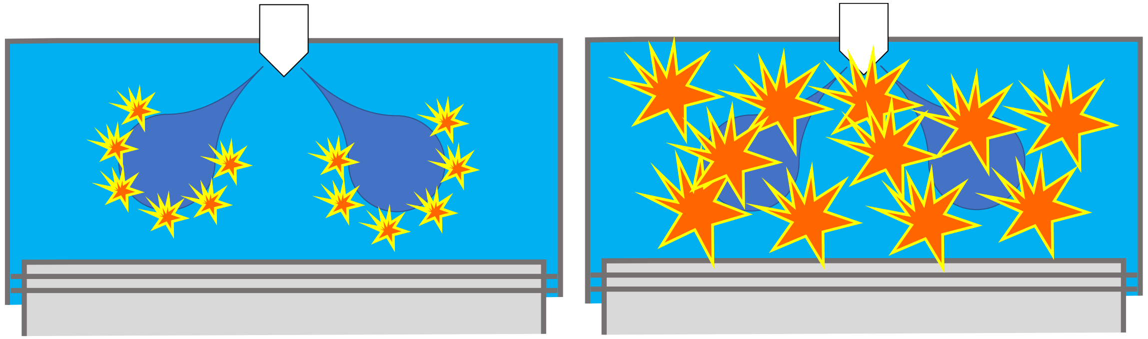
The trigger is not obtained with a different fuel like most of current proposals (RCCI) or by the ignition of a rich mixture zone close to the spark plug (Mazda Sky Active X and VW SACI).

The single fuel should have a **high RON (higher than 70)**

- no high pressure injection
- simplified aftertreatment



TCRCI Combustion concept



Possibile operation with conventional gasoline direct injection technology using also biofuels.

- A small amount of heated fuel is required

Cold injection must produce an almost homogeneous mixture

Hot injection fuel temperature variation fro 350 to 500°C depending on engine speed and load.

The fuel heating can occurr before the hot injector or within the injector itself.

The system can have a low-pressure pump for PFI (port fuel injection - cold injection) and high-pressure pump for direct injection (both cold and hot). This is the typical injection system of a conventional GDI engine as pressure higher than 500 bar are not foreseen.
Both a single shot injection or a multiple shots one can be considered.

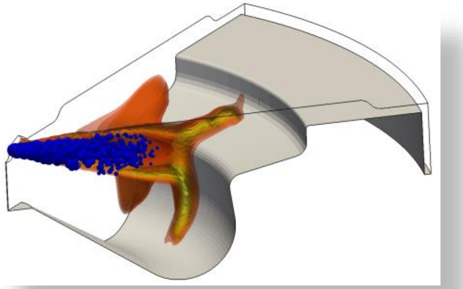
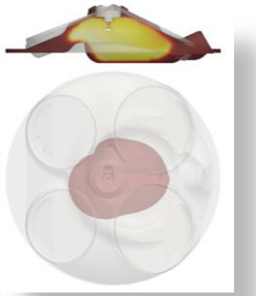
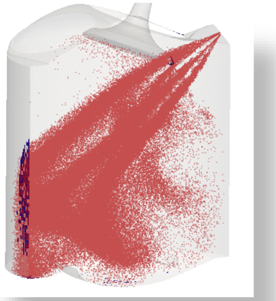
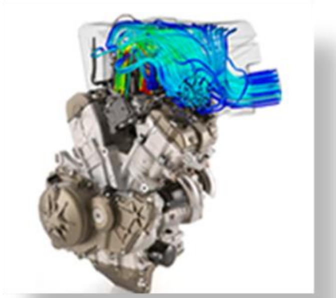
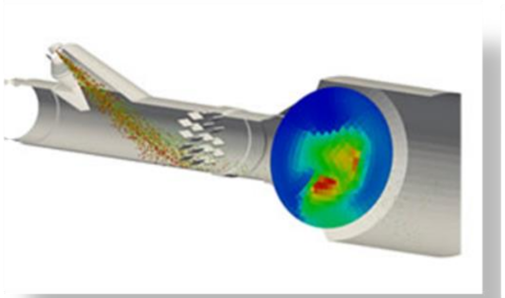
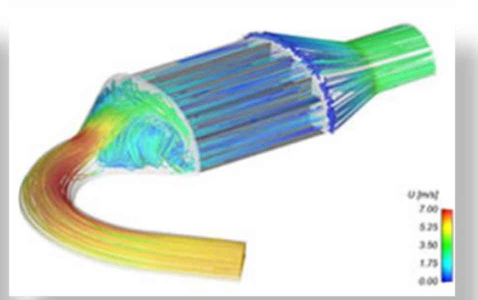
Energy required to heat up the fuel

Percent of Fuel Heated [%] \ Heated Fuel Temperature [deg. C]	200	250	300	350	400	450	500
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.3	0.5	0.6	0.8	1.0	1.2	**1.4**
10	0.5	0.9	1.3	1.7	2.0	2.4	2.8
20	1.1	1.8	2.6	3.3	4.0	4.8	5.5
30	1.6	2.7	3.8	5.0	6.1	7.2	8.3
40	2.2	3.6	5.1	6.6	8.1	9.6	11.1
50	2.7	4.6	6.4	8.3	10.1	12.0	13.8
60	3.2	5.5	7.7	9.9	12.1	14.4	16.6
70	3.8	6.4	9.0	11.6	14.2	16.7	19.3
80	4.3	7.3	10.3	13.2	16.2	19.1	22.1
90	4.9	8.2	11.5	14.9	18.2	21.5	24.9
100	5.4	9.1	12.8	16.5	20.2	23.9	27.6

Fuel Energy [%]
0
5
10
15
20
25
30

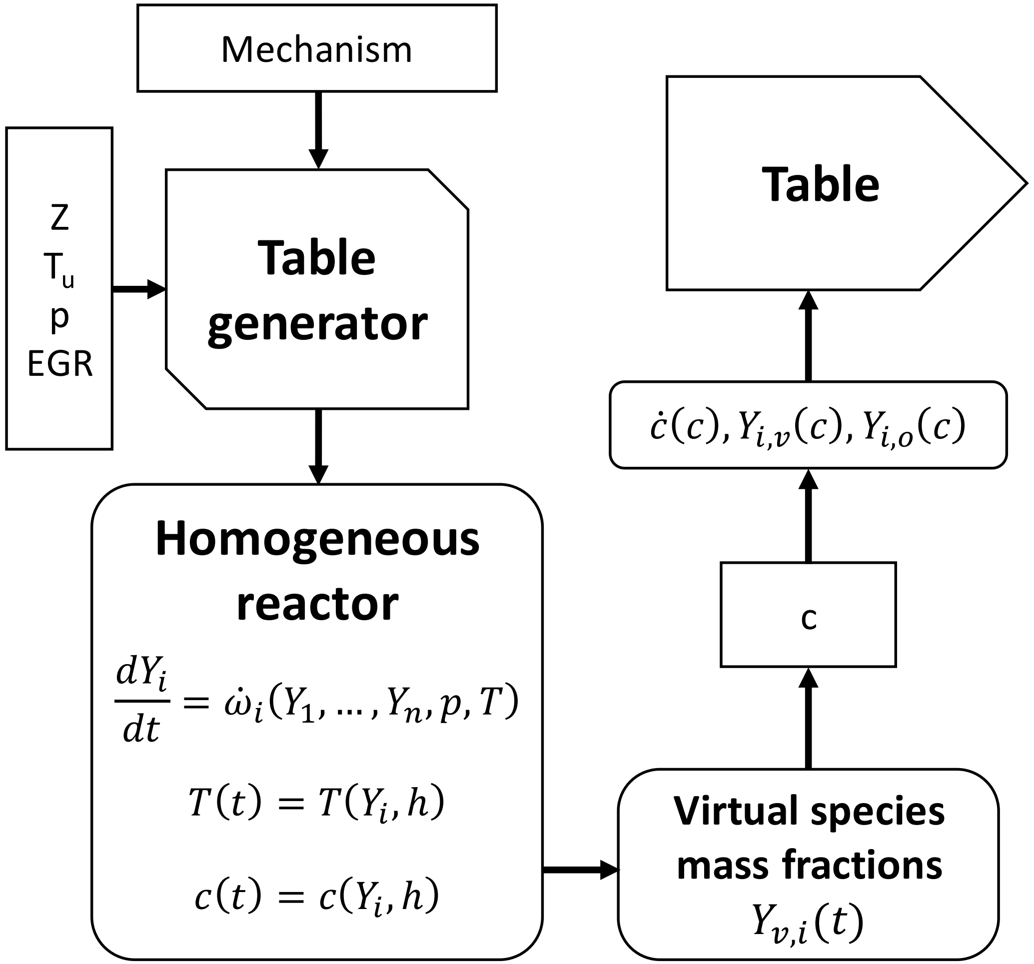
CFD simulations: Lib-ICE

- Set of libraries and solvers for IC engine modeling using OpenFOAM technology:
    - ➢ Mesh motion for complex geometries
    - ➢ Combustion
    - ➢ Lagrangian sprays + liquid film
    - ➢ Unsteady flows in intake and exhaust systems: plenums, silencers, 1D-3D coupling.
    - ➢ Reacting flows in after-treatment devices: DPF, catalyst, SCR.

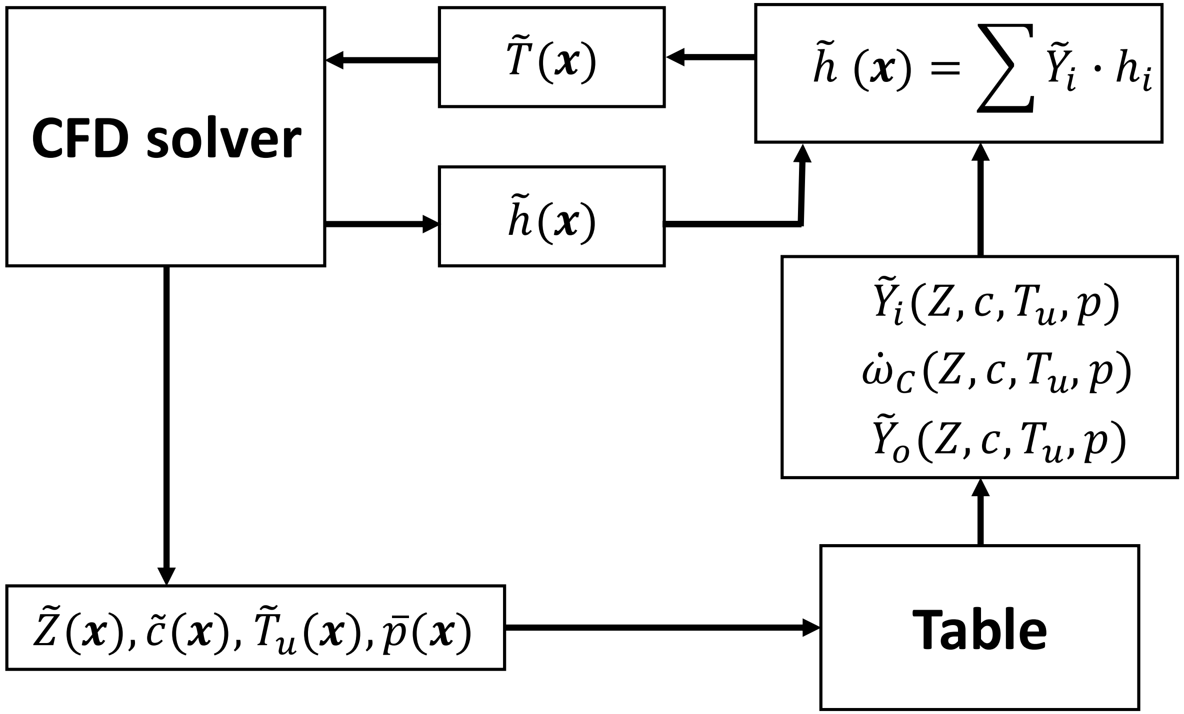
CFD modelling of TCRCI/RCCI combustion process

Tabulated kinetics (single or dual fuel of variable composition): **Lookup table generator**



CFD solver: tabulated kinetics ensures reduced computational time and results accuracy:

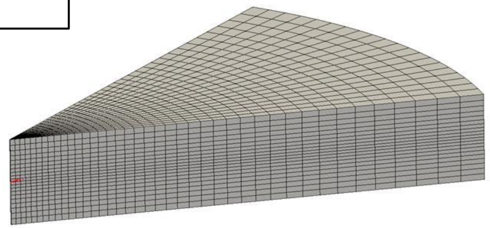
- <u>suitable tool to study and design engines with advanced combsution concepts.</u>



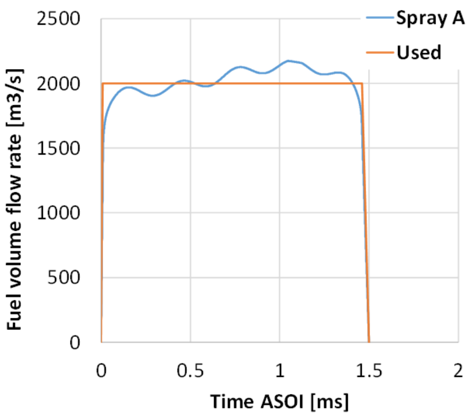
TCRCI assessment at constant volume conditions

Mesh

1/8 of the combustion chamber volume



Injection



Injection Pressure [bar]	**500**
Injection Temperature [K]	**400, 500, 540**
Nozzle diameter [μm]	**90, 150**

- **CDC Fuel: n-$C_{12}H_{26}$ Diesel surrogate**
- **TCRCI Fuel: Gasoline surrogate (56% iso-octane, 28% toluene, 17% n-heptane)**
- **Mechanism: CDC: Yao TCRCI: Frassoldati**

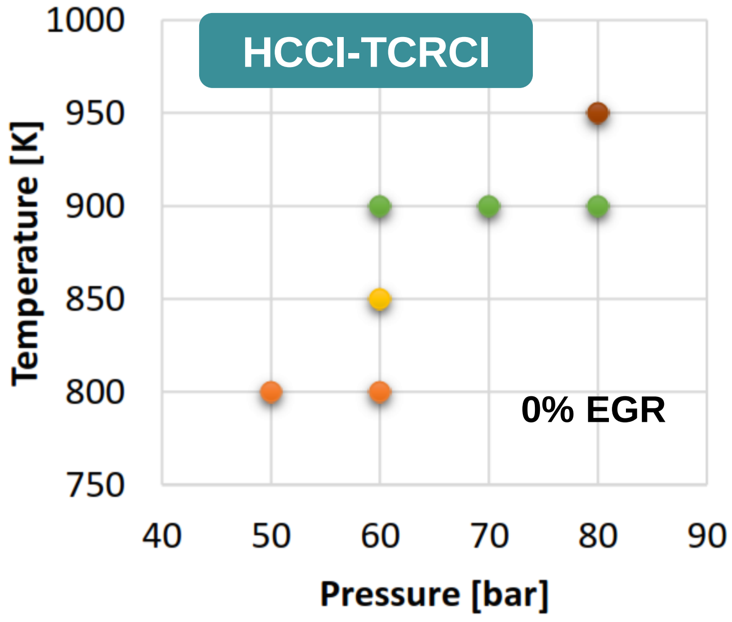
Pressure [bar]	**20-250 (step 30)**
Temperature [K]	**600-1300 (step 50)**
Equivalence Ratio	**0-3 (finer resolution close to ϕ=1)**

Ambient conditions

CDC

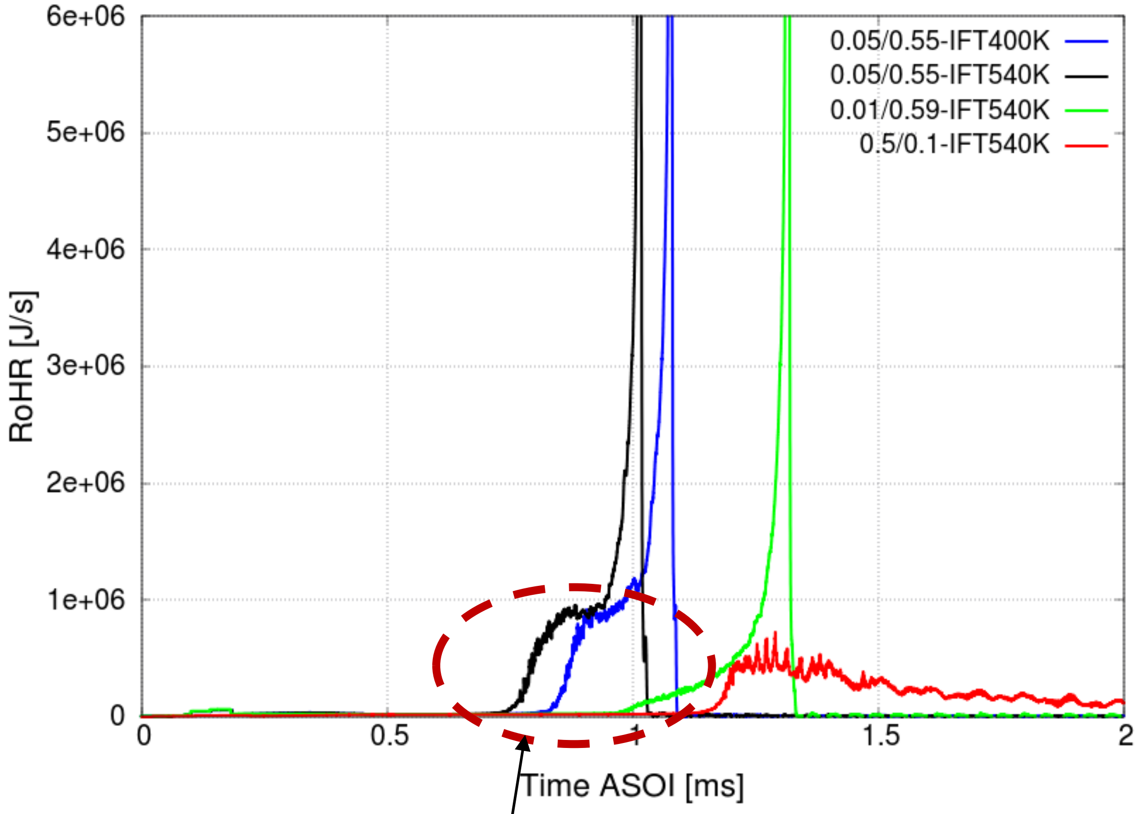
T 900 K
P 60 bar
40% EGR

Reference



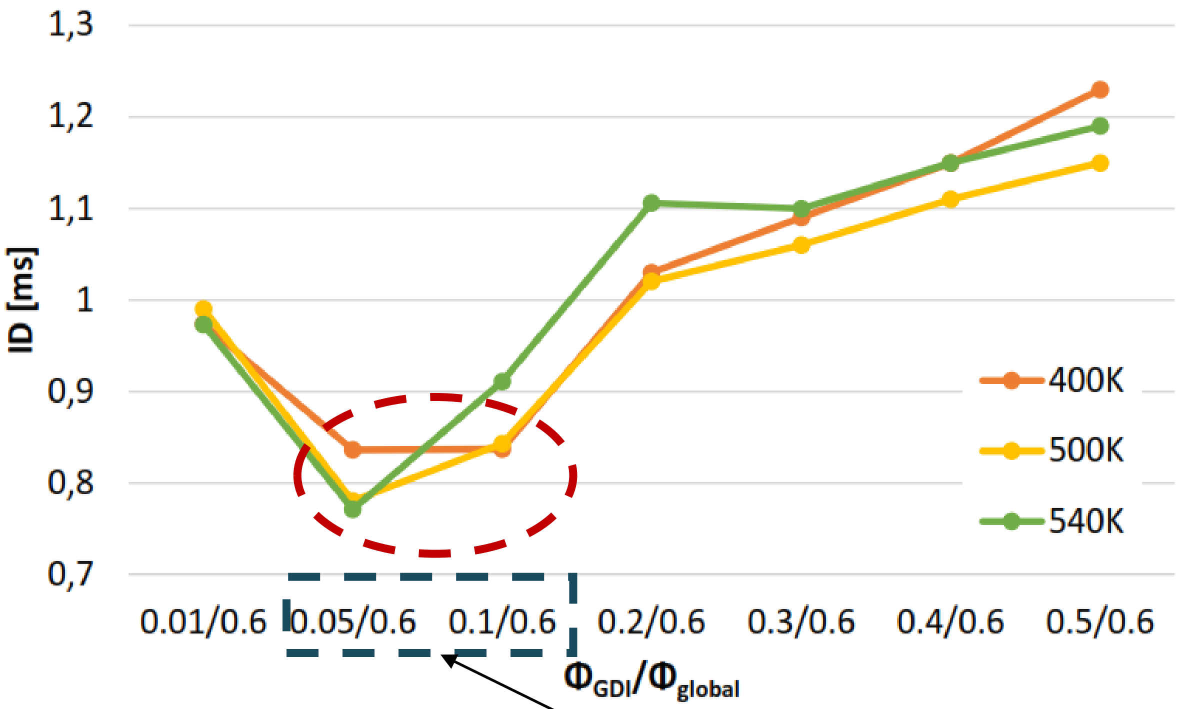
TCRCI assessment at constant volume conditions

RoHR



Heated injection benefits

Ignition Delay



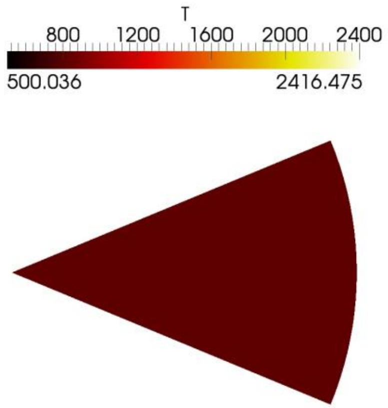
GDI/PFI

Optimal condition

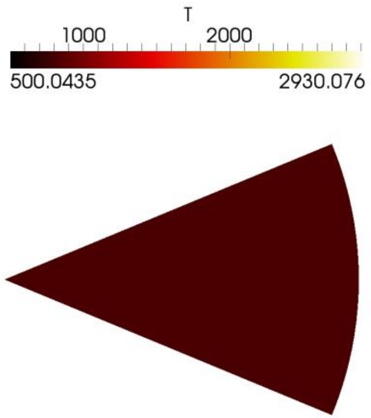
TCRCI assessment at constant volume conditions

TCRCI

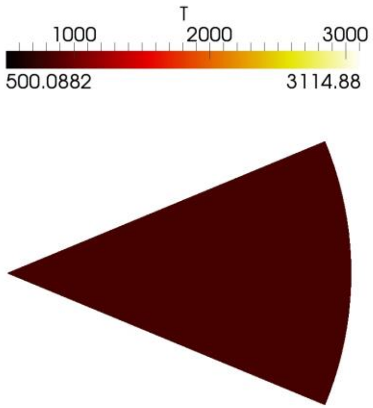
CDC



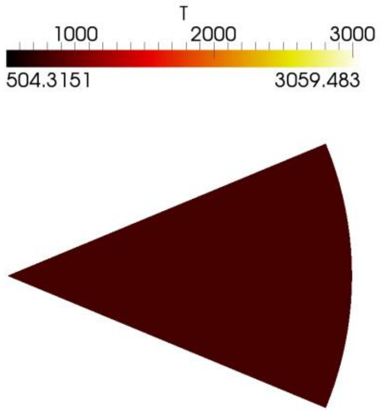
PFI-0.5/GDI-0.1



PFI-0.05/GDI-0.55



HCCI



Similar ignition delay times

Key: PFI/GDI fuel ratio optimization + Heated injection

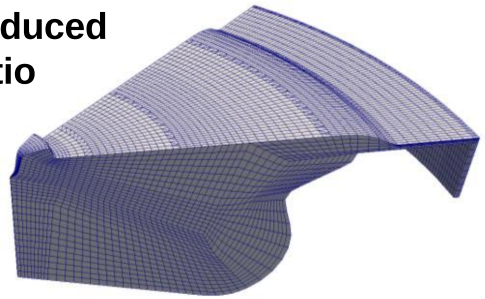
Combustion controllability – In-cylinder fuel stratification at the SOC - Level of soot/NOx

Ignition Dwell - Knocking conditions

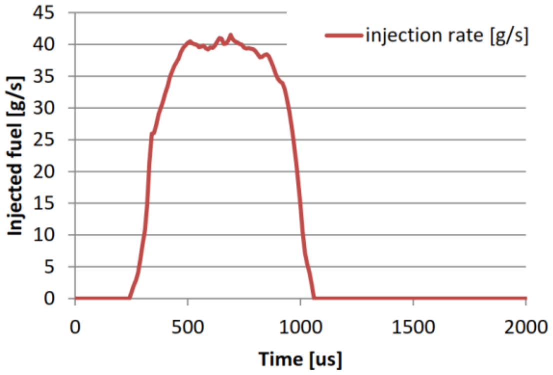
Light-duty engine: combustion mode comparison

Simulation set-up

Mesh
1/8 of the combustion chamber with reduced compression ratio



Injection



SOI [CAD]	-25
Injection Pressure [bar]	1550
Injection Temperature [K]	313
DI mass [mg]	3.22

PCCI

- **Fuel: n-C_7H_{16} Diesel surrogate**
- **Mechanism: Curran (159 species)**

n [rpm]	2000
BMEP [bar]	5
p@IVC [bar]	1.3
T@IVC [K]	403.52
EGR	~40%
Equivalence Ratio	~0.8

RCCI/TCRCI/HCCI

- **Fuel:**
  - **DI: n-C_7H_{16} (RCCI) or Gasoline surrogate (TCRCI)**
  - **PFI: Gasoline surrogate**
- **Mechanism: Faravelli (156 species)**

SOI [CAD]	variable
Injection Pressure [bar]	500
Injection Temperature [K]	500
DI mass [mg]	0-3.22

n [rpm]	2000
BMEP [bar]	5
Pressure at IVC [bar]	1.3
Temperature at IVC [K]	403.52
EGR	0%
Equivalence Ratio	0-0.42

Light-duty engine: RCCI combustion evaluation

SOI at high temperature optimization

+

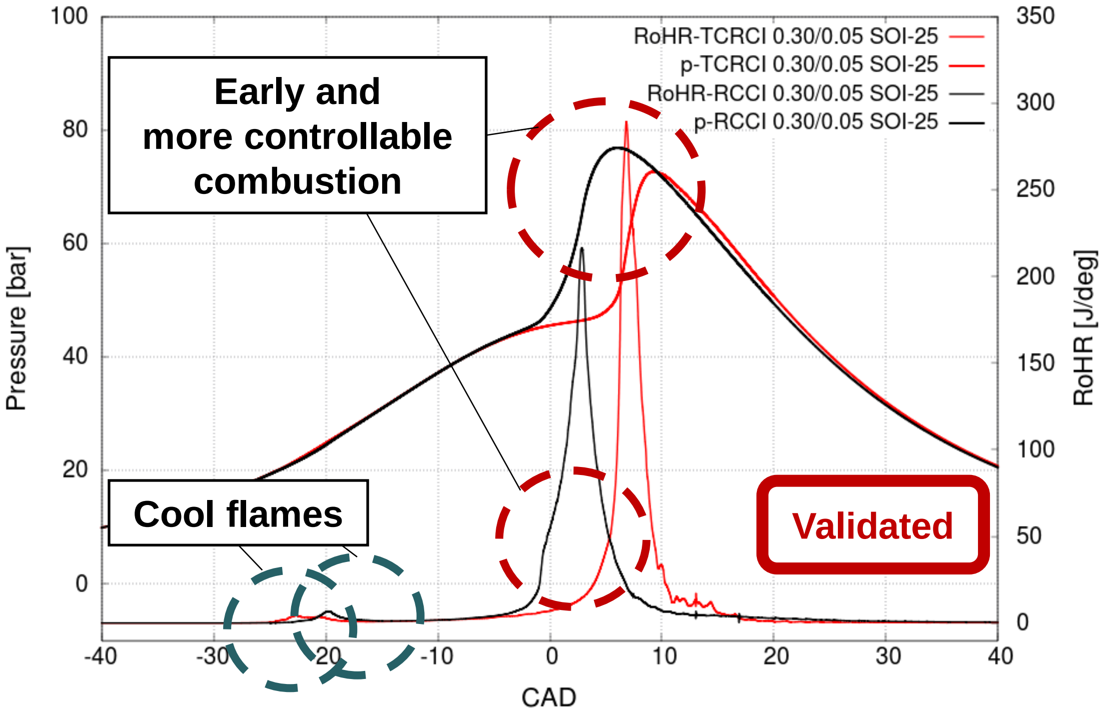
PFI/GDI fuel ratio optimization

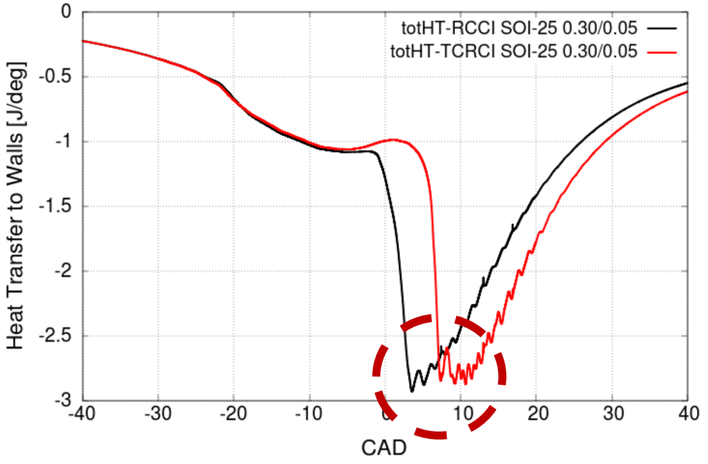
=

GIE > 45%

Φ_{PFI-DI}	θ	dp/dθ	MFB50	SOI	Work [J]	Q_{comb} [J]	G.I.E.
0.30+0.05	0.1°	4,92E+05	0.3°	-35.1°	381,526	843	45,25%
0.30+0.05	1.55°	1,12E+06	1.665°	-30.1°	395,334	870	45,42%
0.30+0.05	2.8°	1,08E+06	3.085°	-25.1°	394,576	869	45,38%
0.26+0.09	-1.92°	1,6E+06	-1.92°	-30.1°	391,641	872	44,87%

MFB50 near TDC





Heat Transfer losses =

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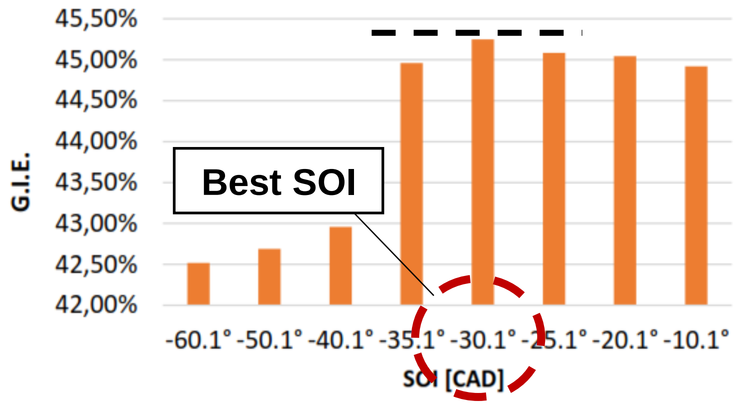
Light-duty engine: TCRCI combustion evaluation

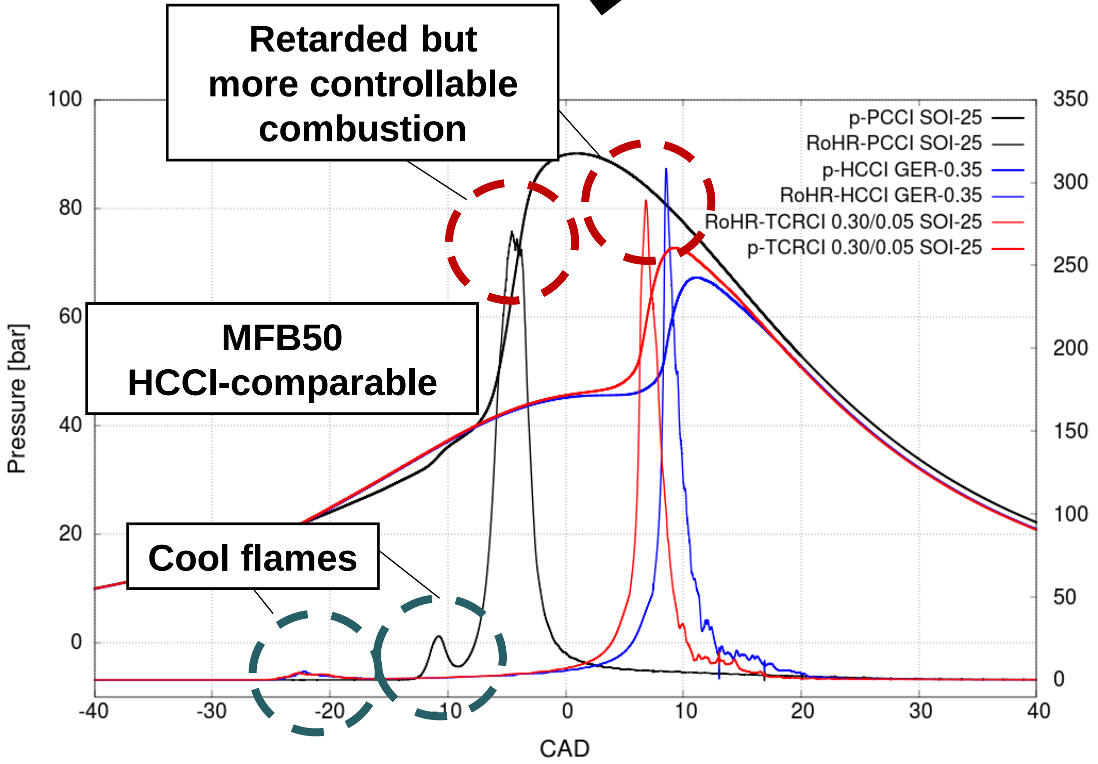
SOI at high temperature optimization

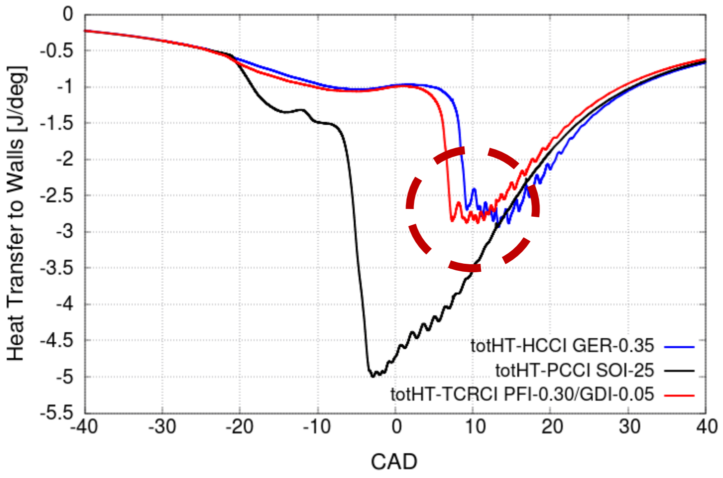
+

PFI/GDI fuel ratio optimization

GIE > 45%







Heat Transfer losses

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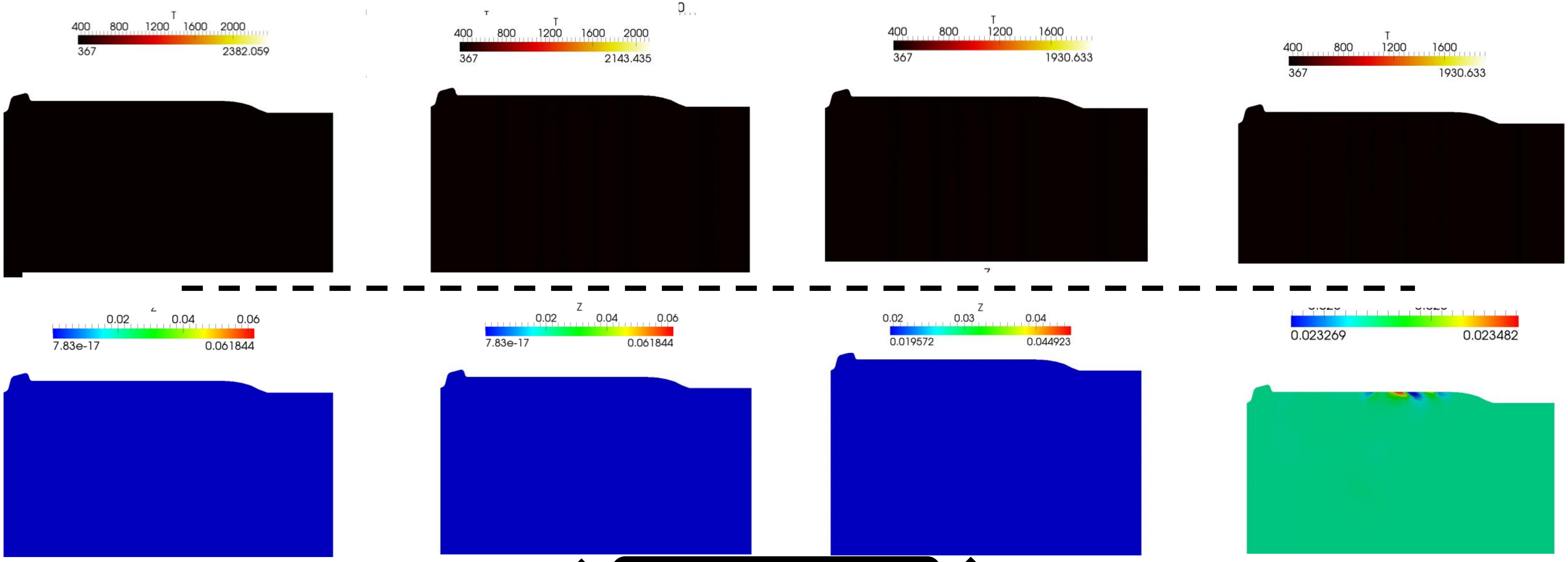
L. Marmorini

Light-duty engine: comparison of combustion modes

PCCI | **RCCI** | **TCRCI** | **HCCI**



Different fuels ← **Reactivity-controlled** → **Heated injection**

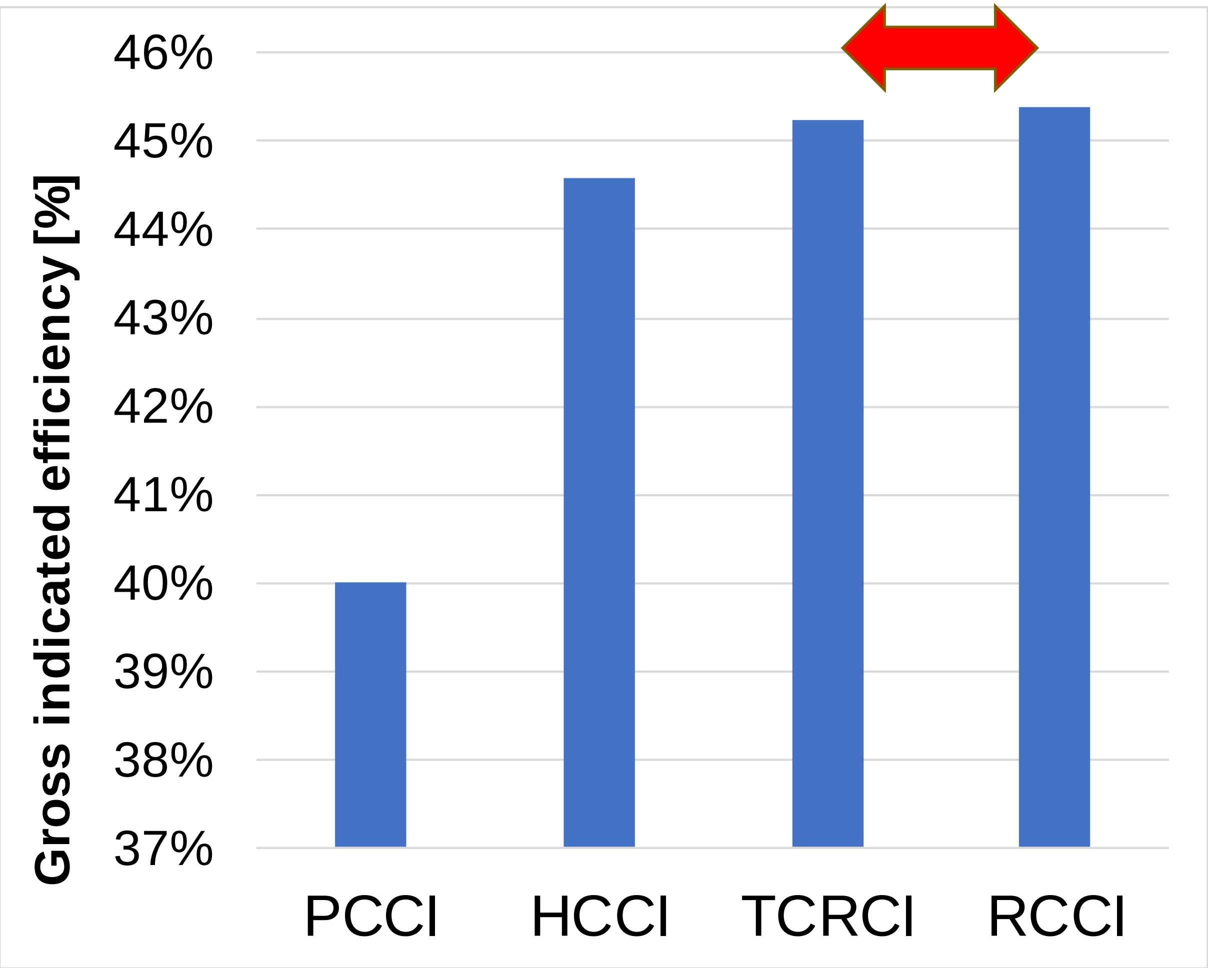
Combustion controllability – In-cylinder fuel stratification at the SOC - Level of soot/NOx

Light-duty engine: comparison of combustion modes

Summary

Promising results of single-fuel TCRCI combustion feasibility in the light of heated injection control.

TCRCI is RCCI-comparable in terms of:
- efficiency;
- auto-ignition control;
- pollutant emissions.

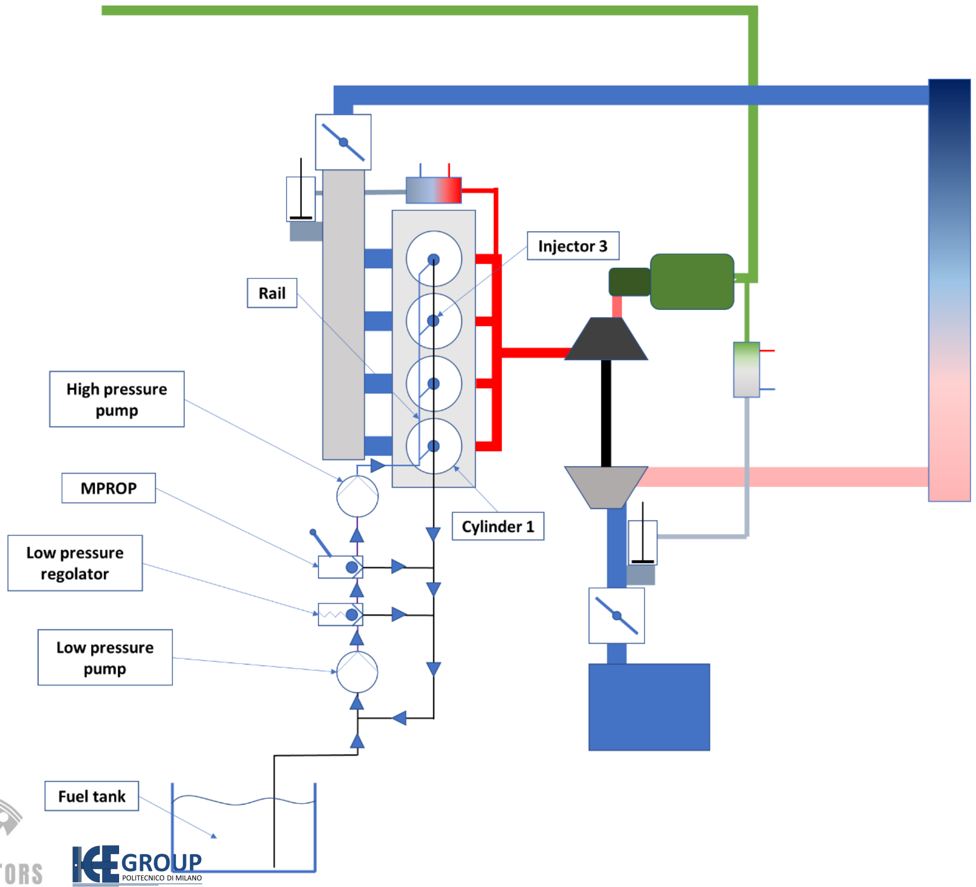


TCRCI/RCCI engine experiments

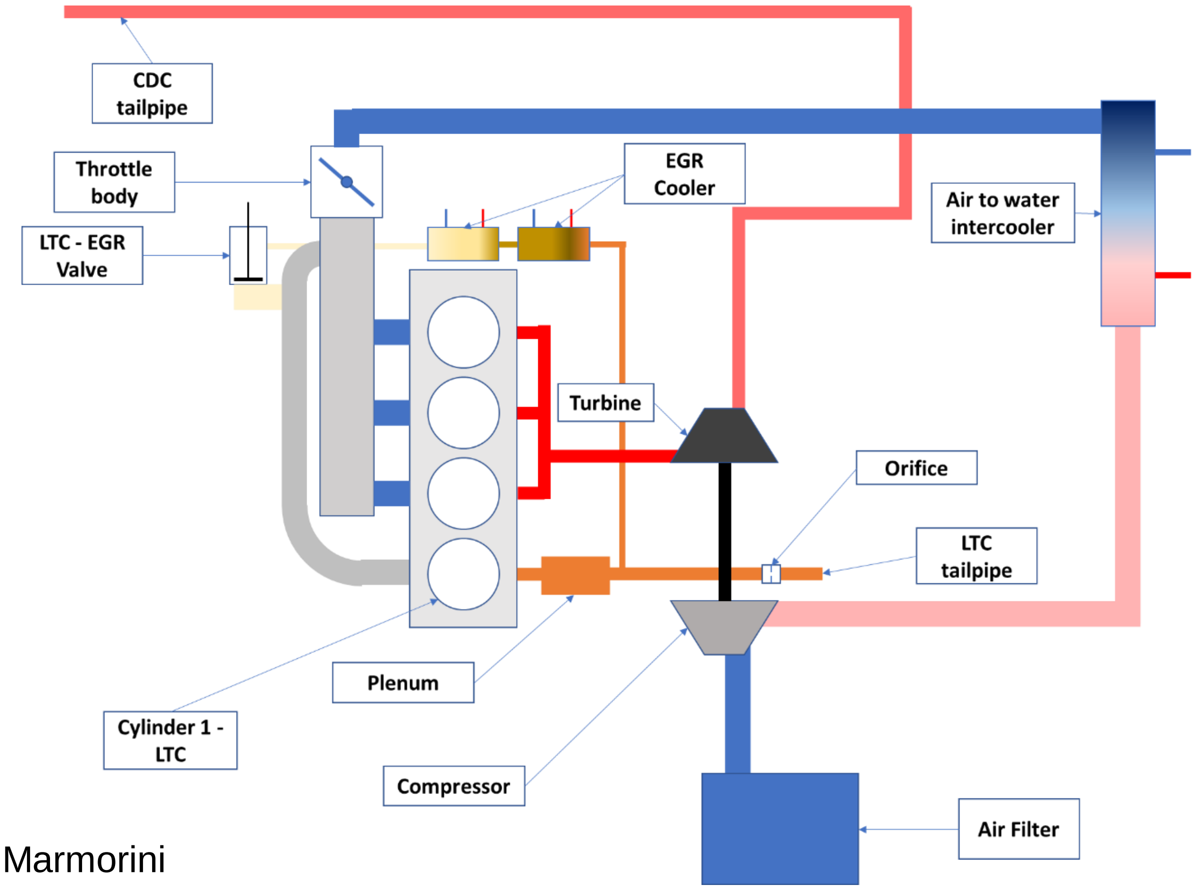
- Development of an Open ECU (Spark – Alma Automotive)
- Transition from Bosch ECU to Spark ECU

- **3+1 Engine** (retrofit of a commercial 2.0 lt. JTD FCA engine)
- Tests in RCCI and TCRCI mode

Base engine

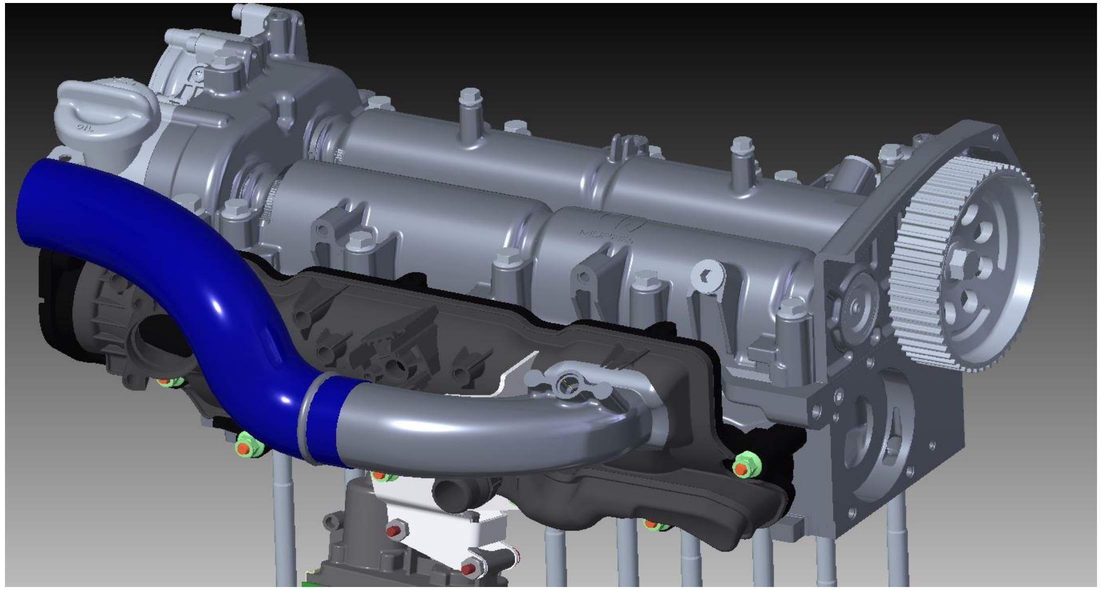


Modified engine (3+1)

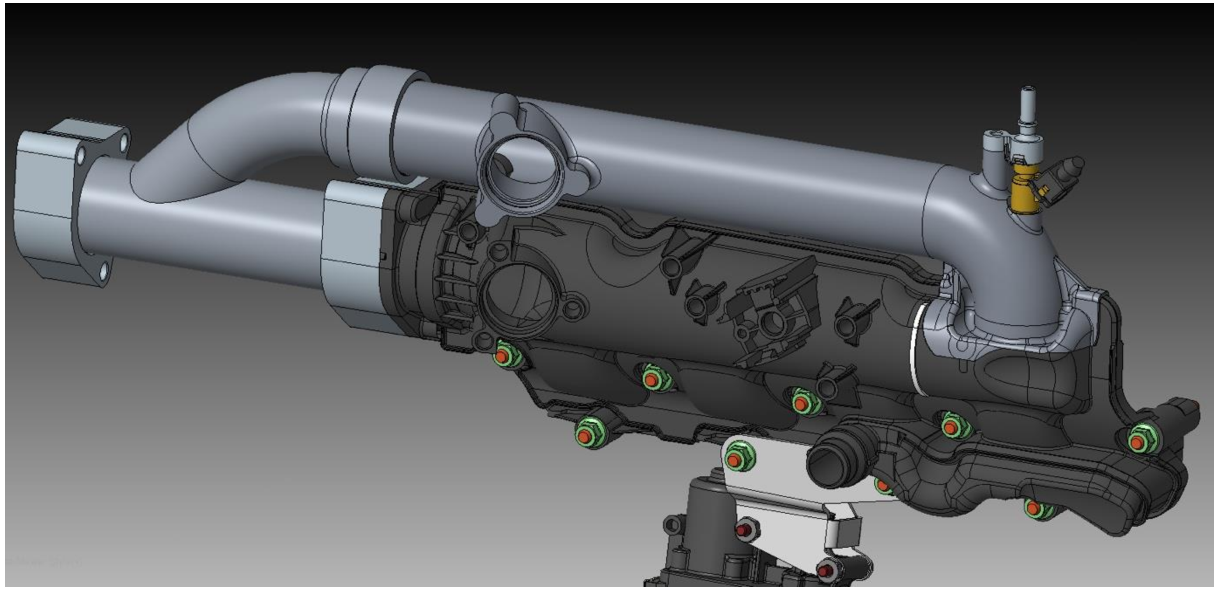


TCRCI/RCCI engine experiments

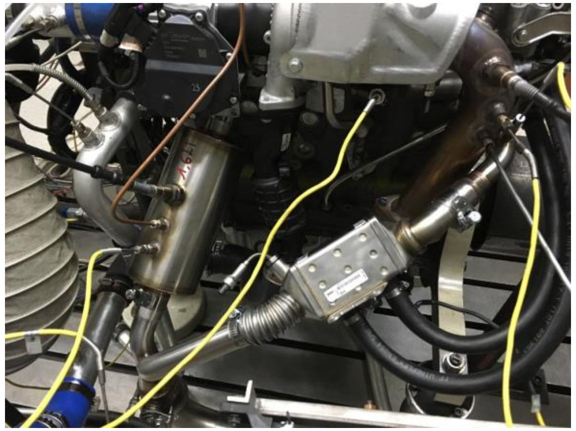
Modified inlet collector

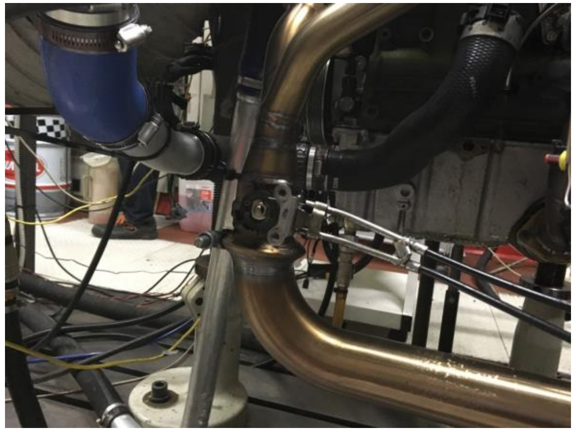


PFI Injection system



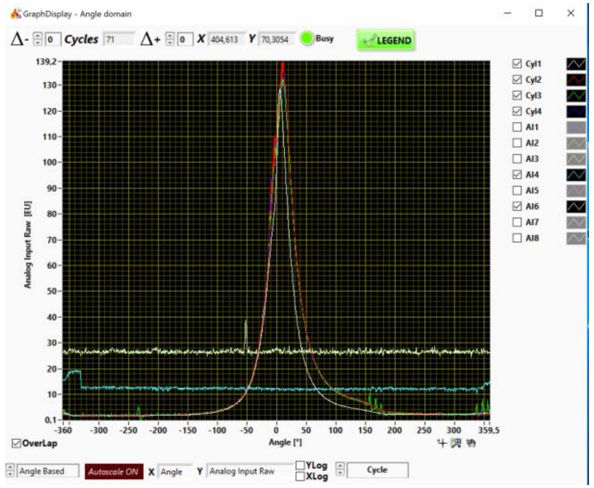
Test cell layout



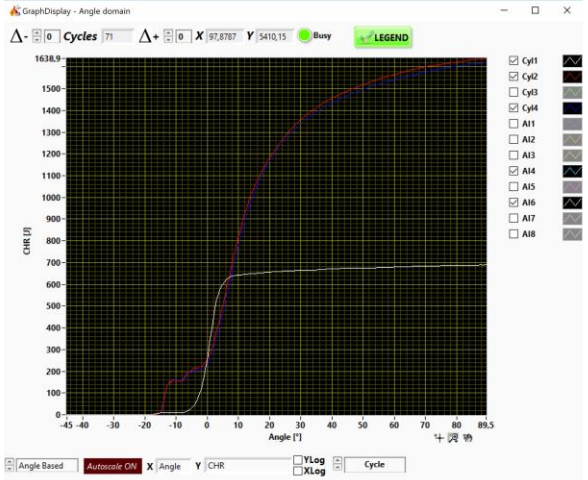


RCCI Experiments

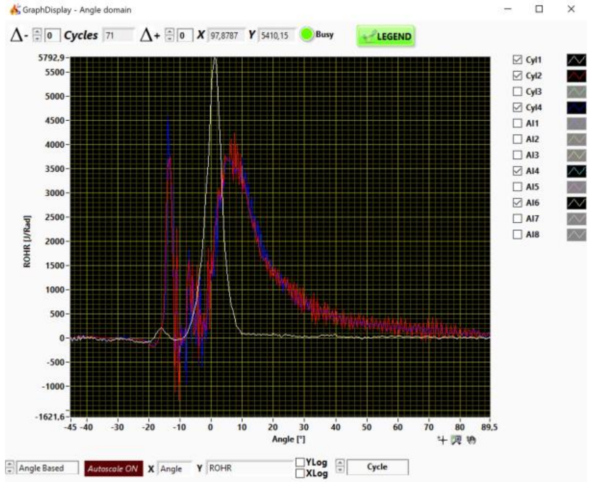
Indicated data



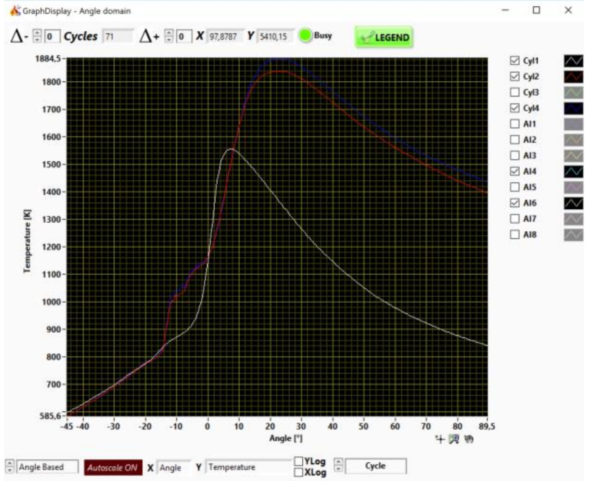
Pressure



Cum. HRR

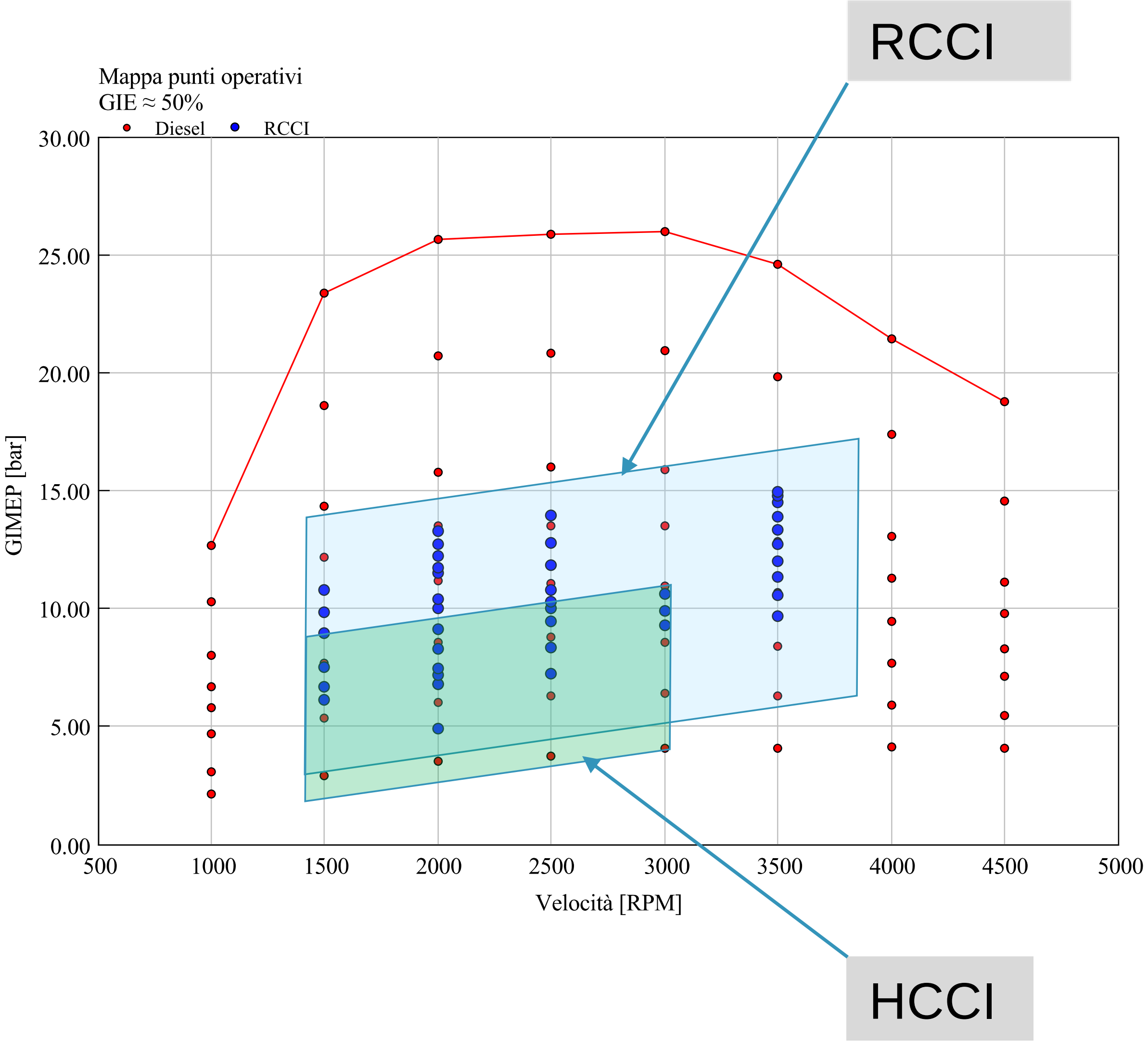


Heat release rate



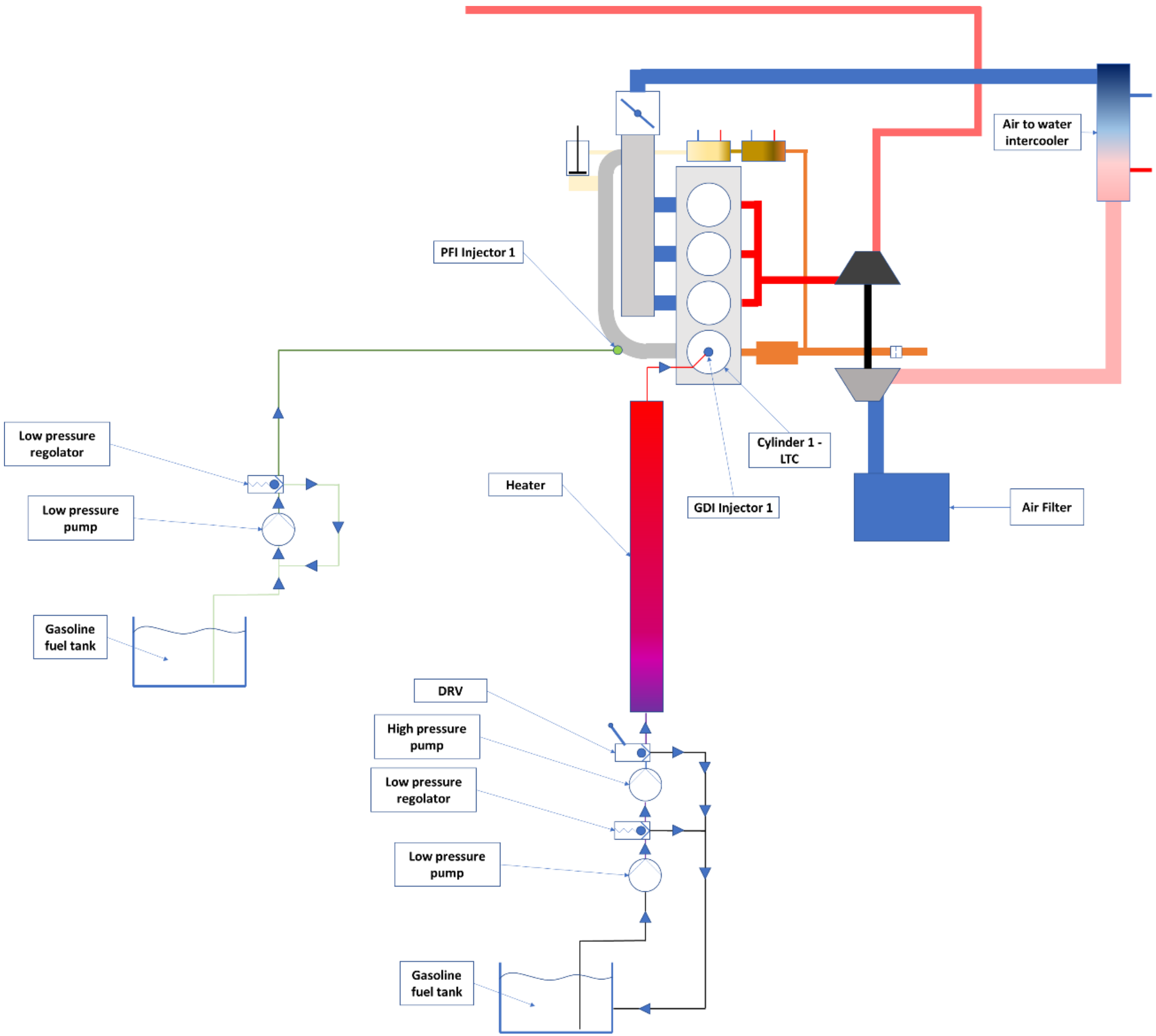
Cyl. temperature

Operating points with G.I.E. higher than 50%

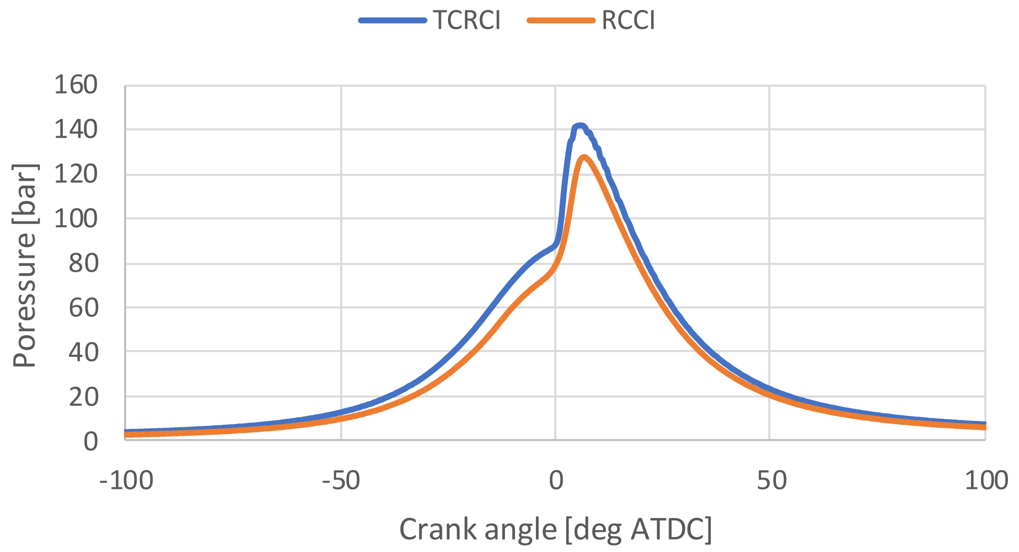


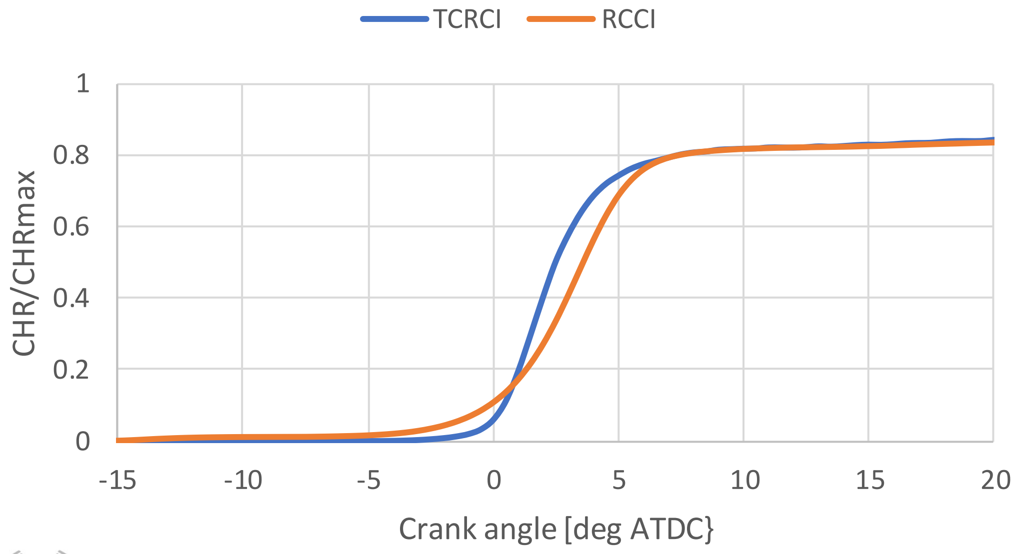
TCRCI Experiments

3+1 Engine (TCRCI Layout)

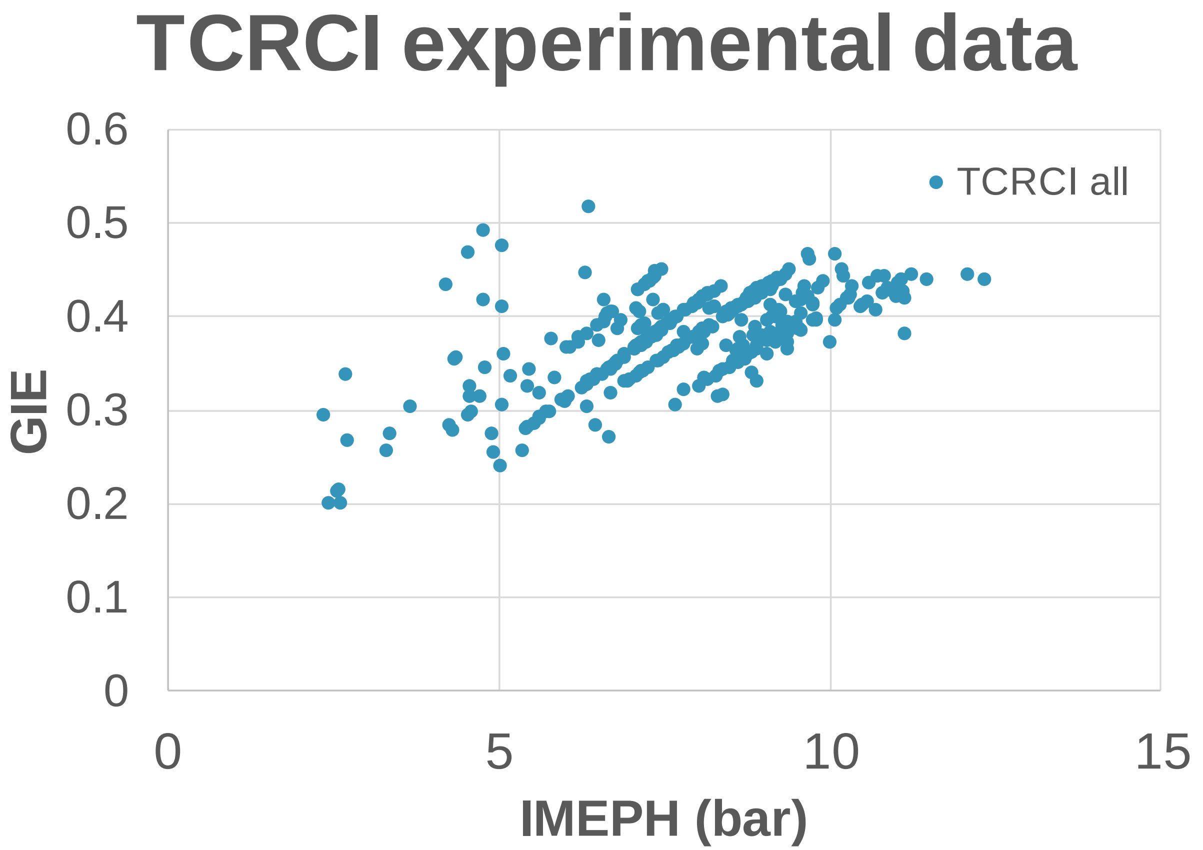


TCRCI vs RCCI Experiments





Gross indicated efficiency as function of the IMEPH



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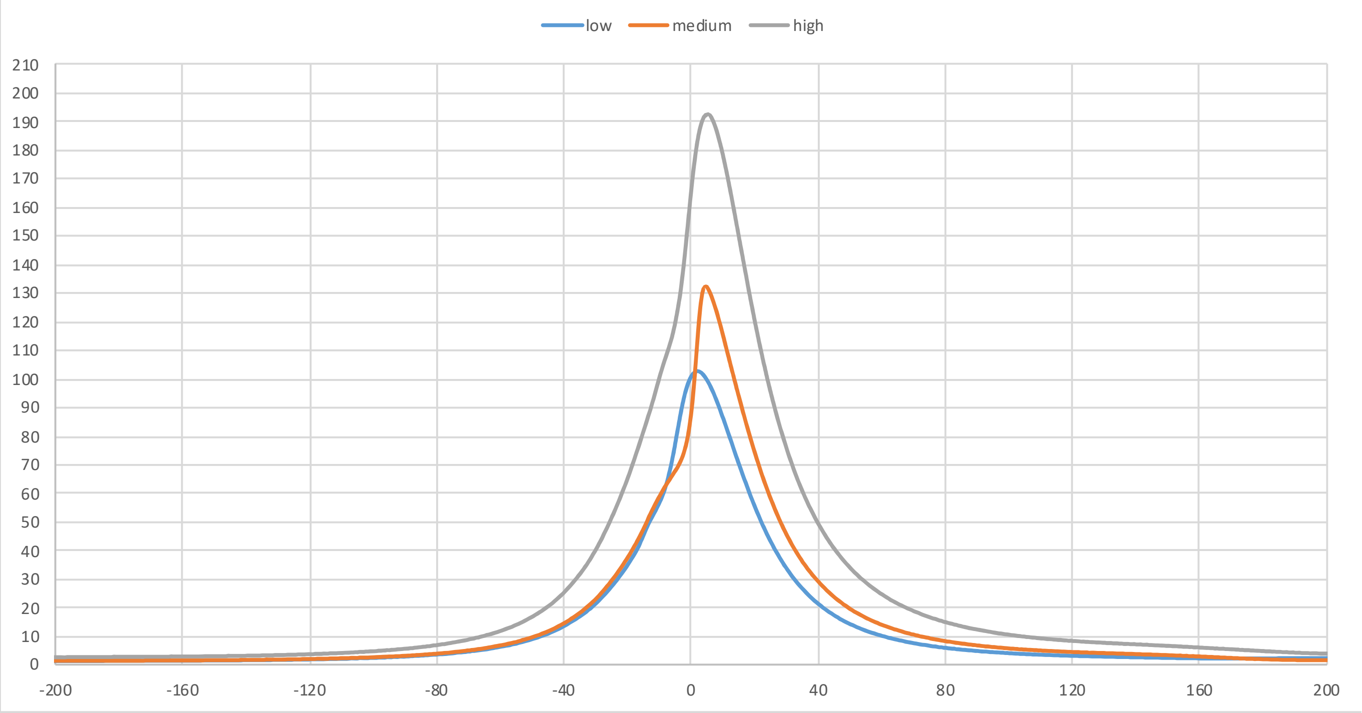
RCCI Engine simulations

	low load		medium load		high load	
test	181018_p12		181024_p6		181017_p27	
GIMEP	4.8	bar	8.8	bar	14.5	bar
RPM	2000	1/min	2000	1/min	3500	1/min
m_inj_tot	10	mg	20	mg	30	mg
PFI	70	%	92	%	82	%
PFI_qty (gasoline)	7	mg	18.4	mg	24.6	mg
DI_qty (diesel)	3	mg	1.6	mg	5.4	mg
split	20	%	30	%	0	%
DI_split1	0.6	mg	0.48	mg	0	mg
DI_split2	2.4	mg	1.12	mg	5.4	mg
SOI1	62	°CA bTDCF	75	°CA bTDCF	-	°CA bTDCF
SOI2	42	°CA bTDCF	55	°CA bTDCF	35	°CA bTDCF
Inj_time1	238	µs	230	µs	-	µs
Inj_time2	311	µs	255	µs	356	µs
T_fuelDI	40	°C	42	°C	43	°C
p_Rail	1095	bar	1210	bar	1600	bar
EGR_ext	0	%	25	%	38	%
EGR_tot (ext+res)	8.3	%	28	%	41	%
O2 mass fraction	0.2261		0.1968		0.1783	
N2 mass fraction	0.7685		0.7659		0.7612	
CO2 mass fraction	0.0039		0.027		0.0438	
H2O mass fraction	0.0015		0.0103		0.0167	
p_IVC (-153°CA)	170000	Pa	170000	Pa	310000	Pa
T_IVC (-153°CA)	350	K	355	K	380	K
lambda	2.885		1.374		1.057	
lambda	5.2		2.1		1.9	
lambda_premix	4.121		1.493		1.289	
phi_premix	0.2426		0.6696		0.7758	

DI Injector geometry		
Inj_n_holes	7	
Spray angle	148	°
D_hole	0.146	mm



Buttitta M., “Analisi teorico sperimentale del Sistema di combustione TCRCI”, Master thesis in Mechanical Engineering, University of Modena and Reggio Emilia, December 2018

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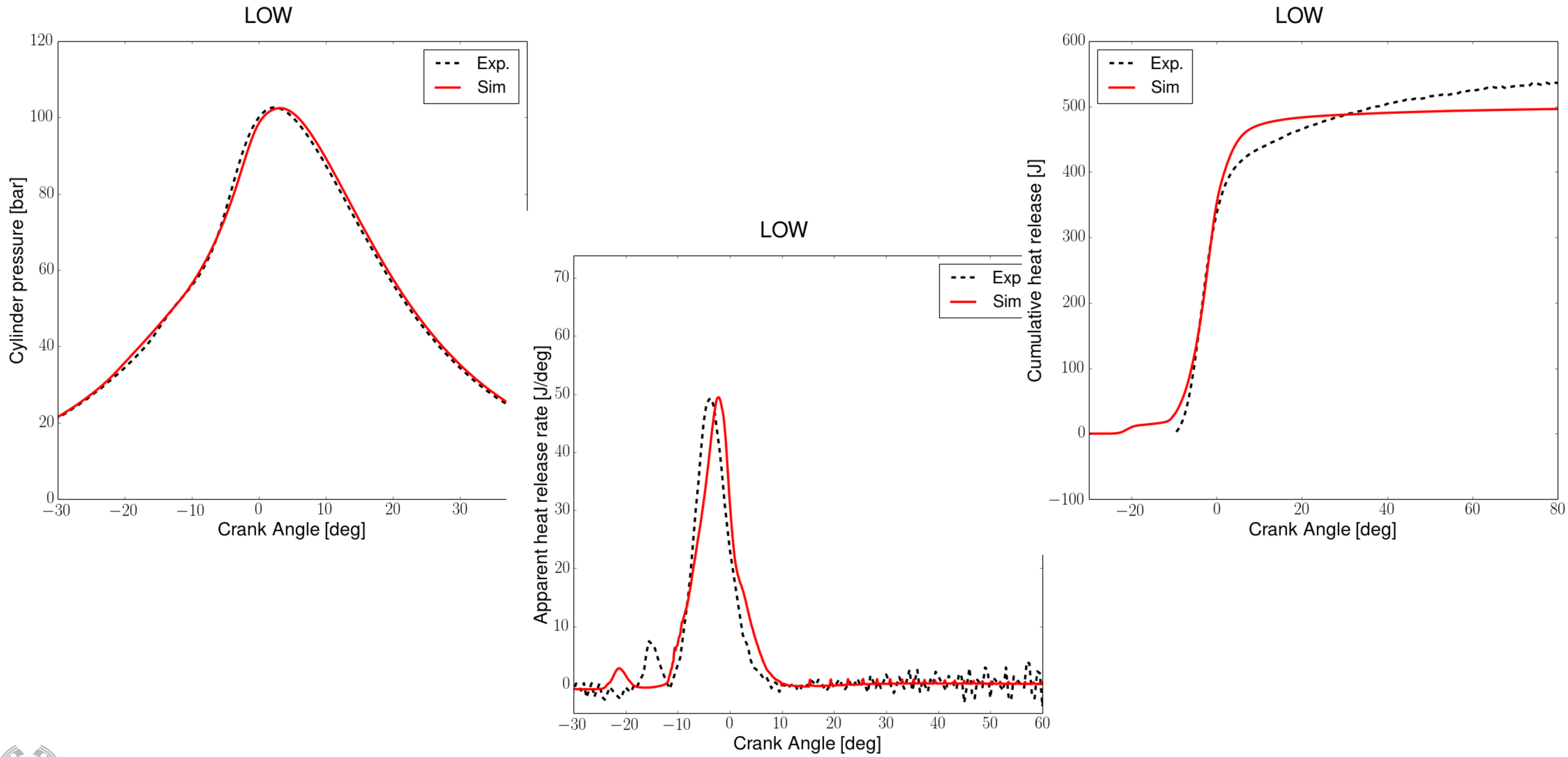
RCCI Engine simulations: Low load



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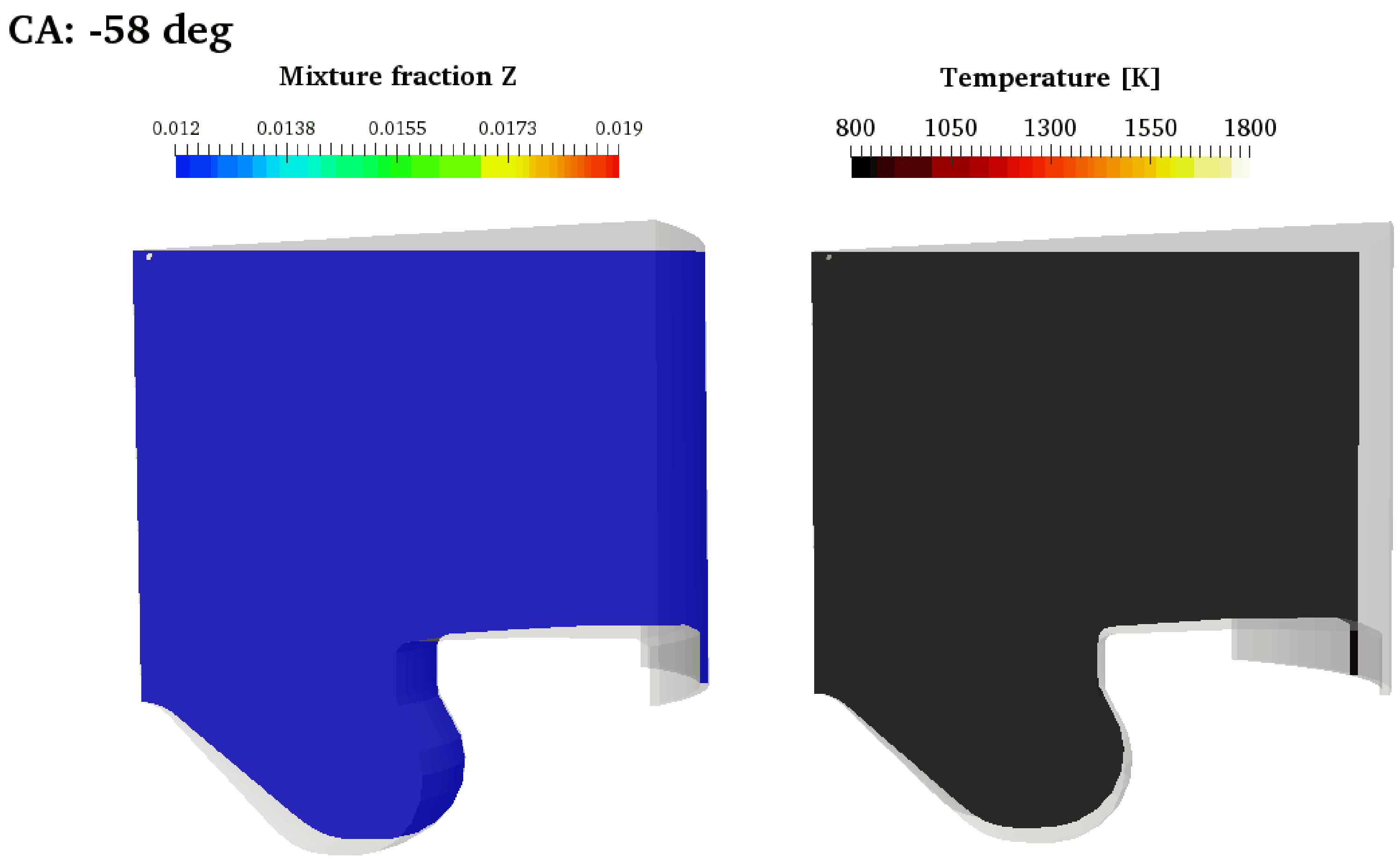
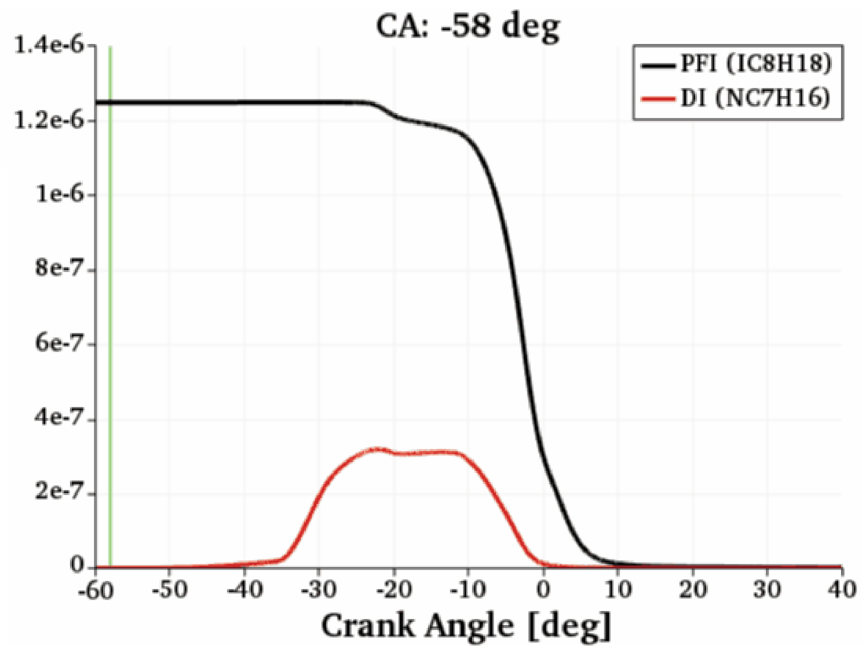
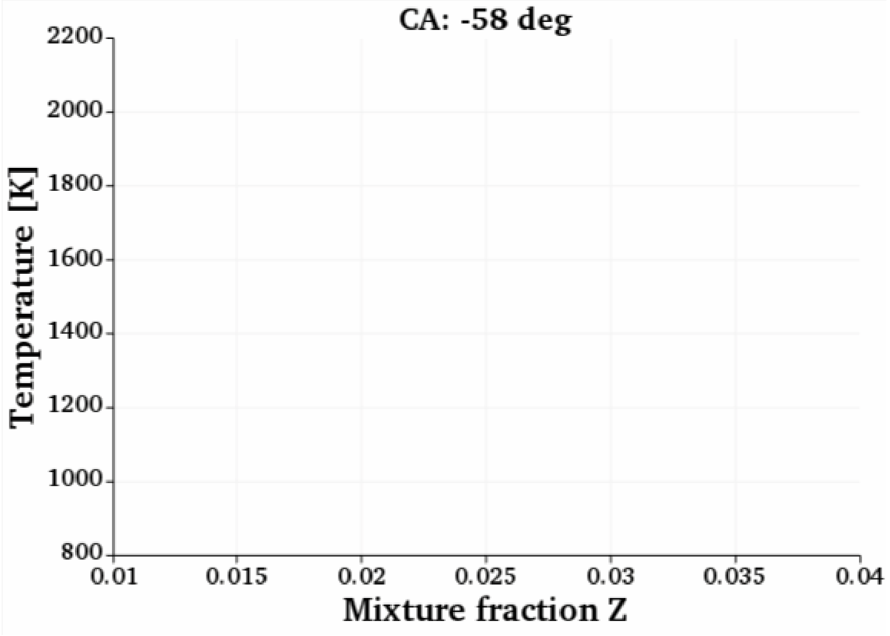
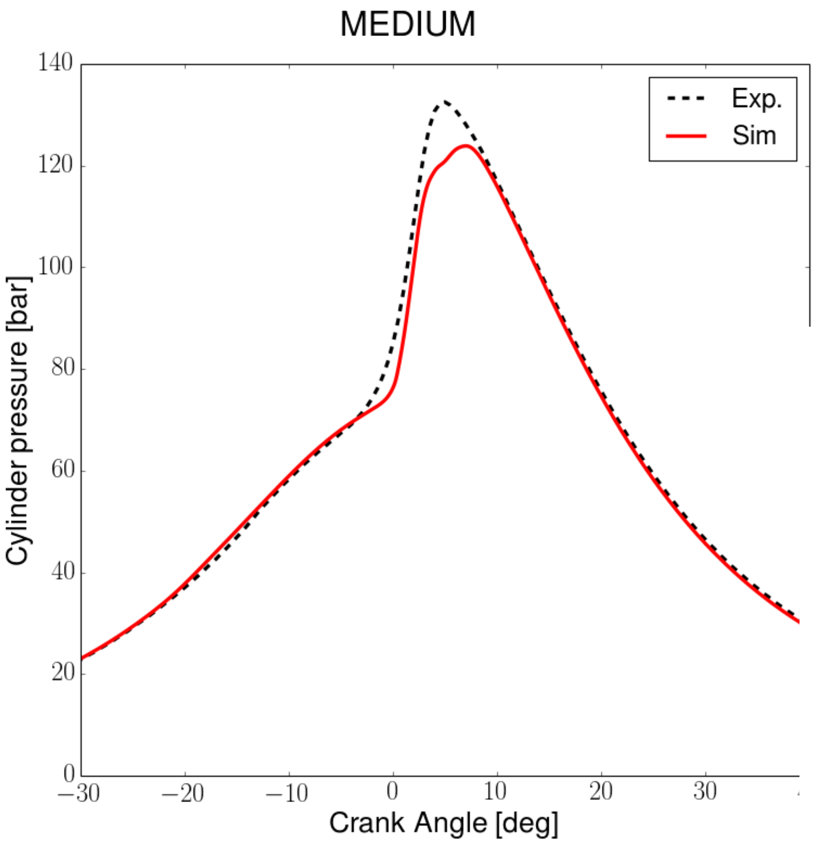
RCCI Engine simulations: Low load

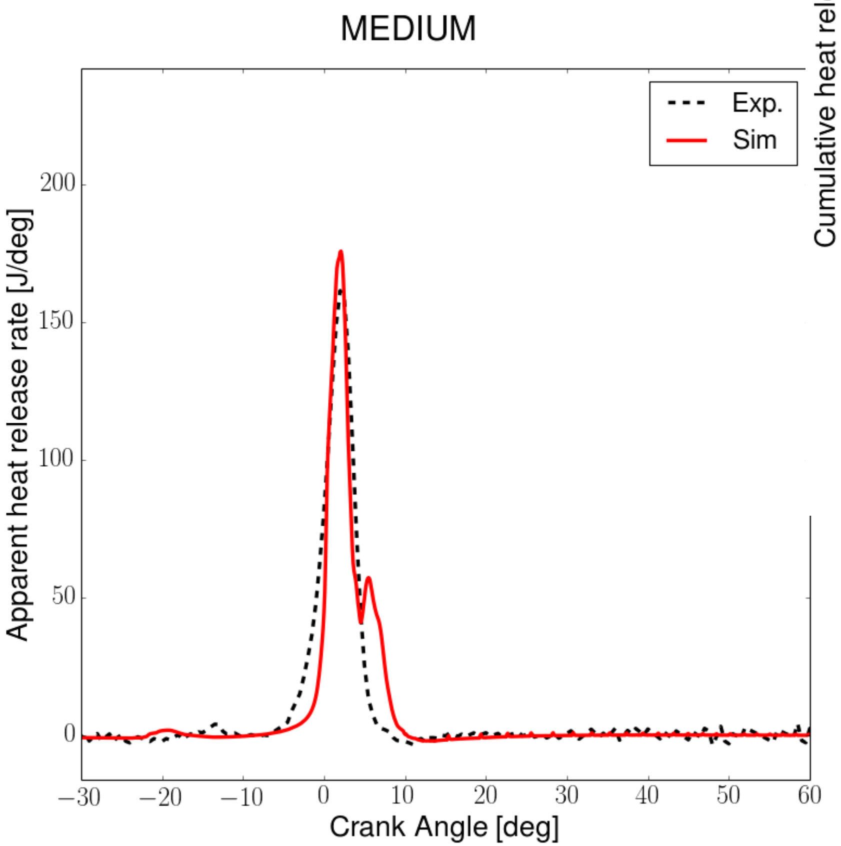


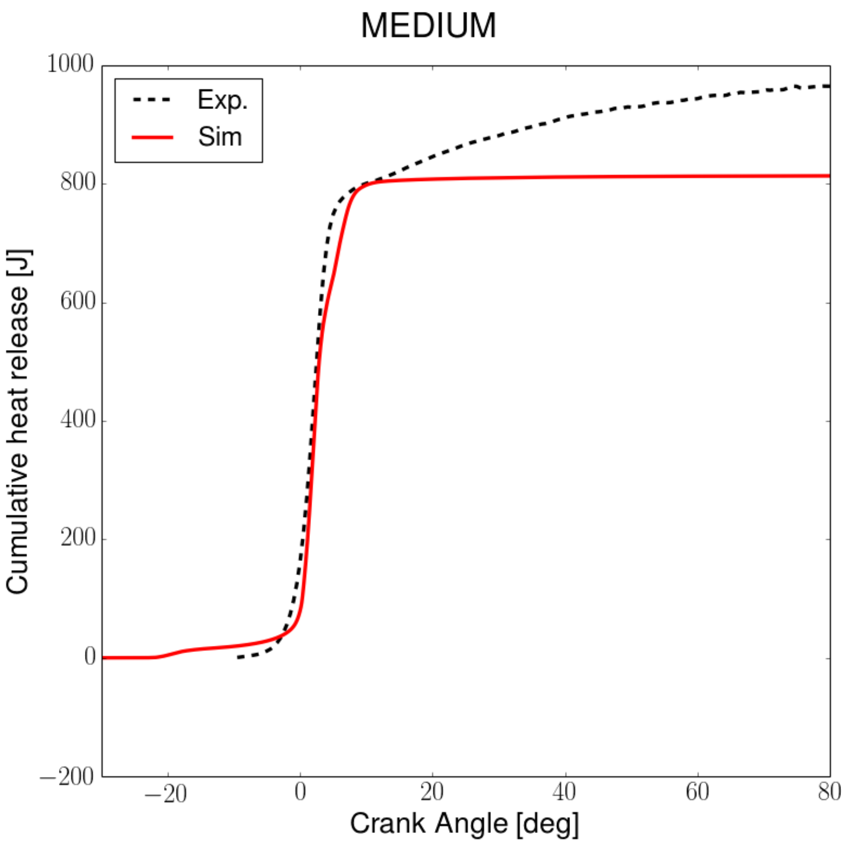




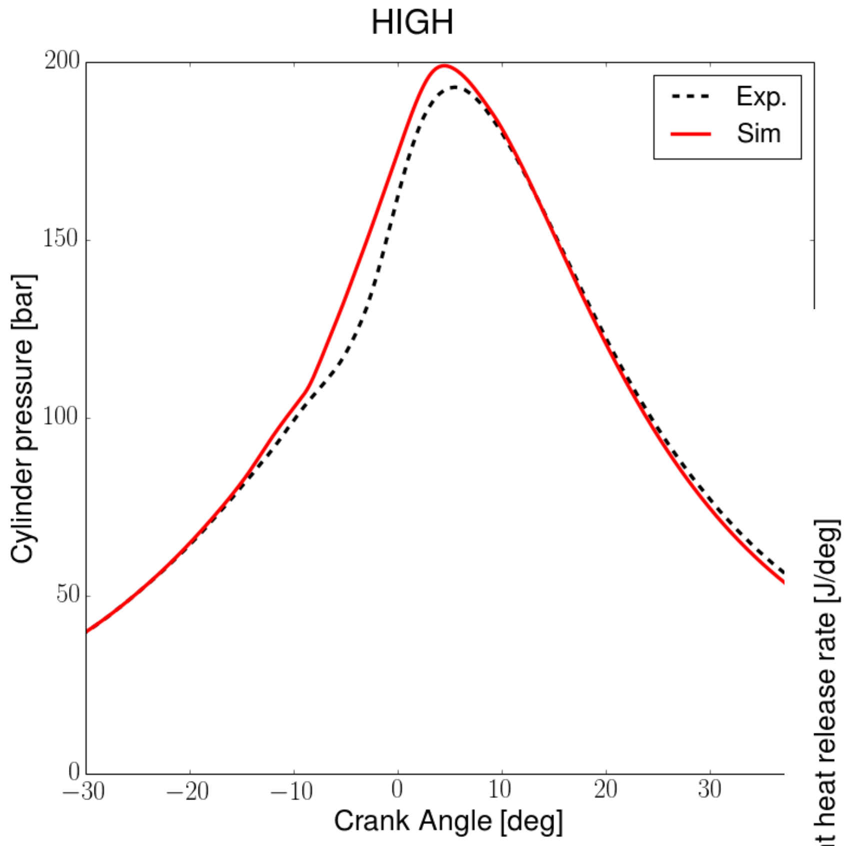
RCCI Engine simulations: Medium load

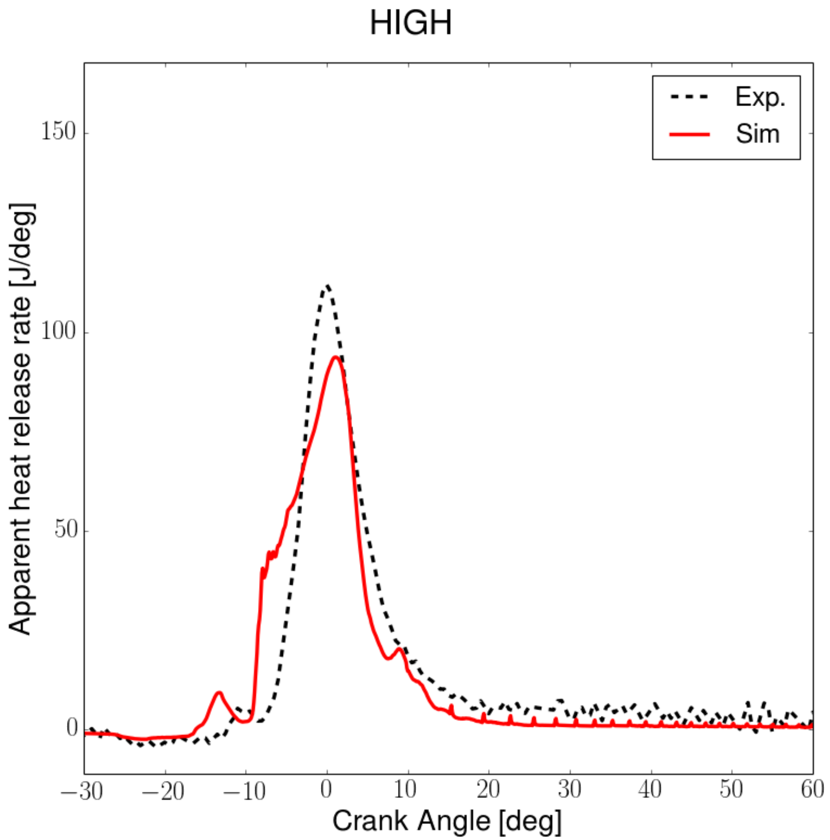


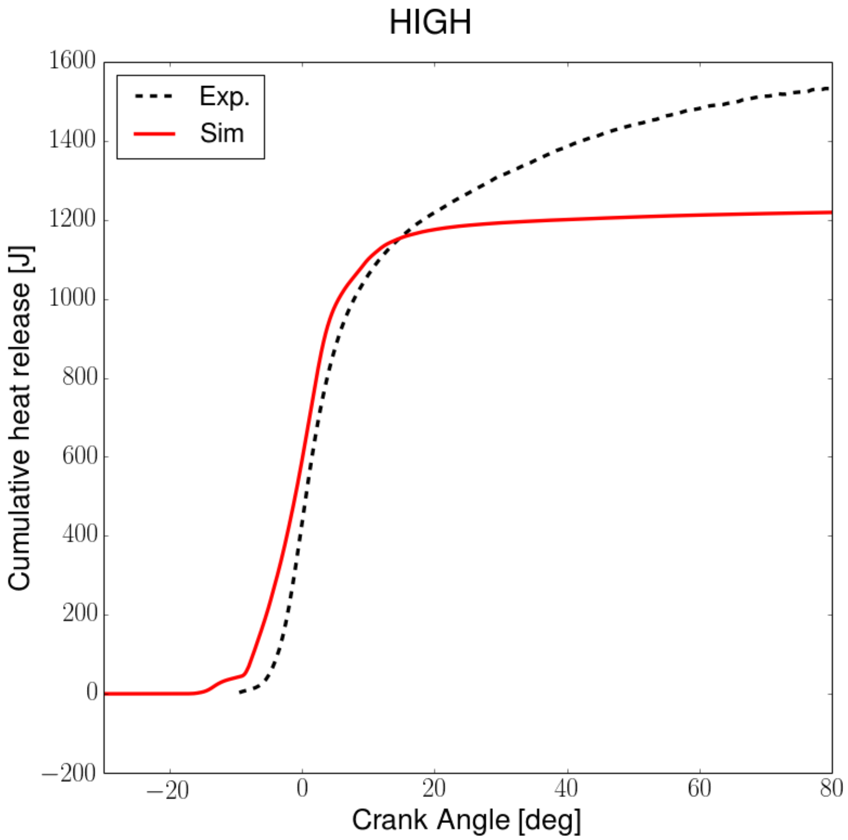




RCCI Engine simulations: High load







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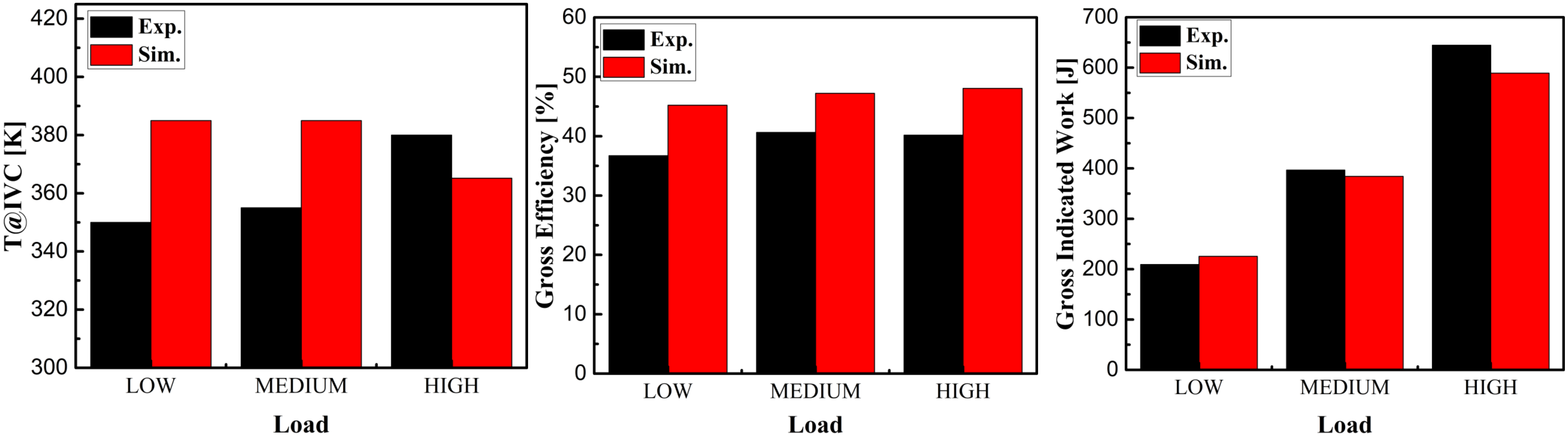
RCCI Engine simulations: results summary



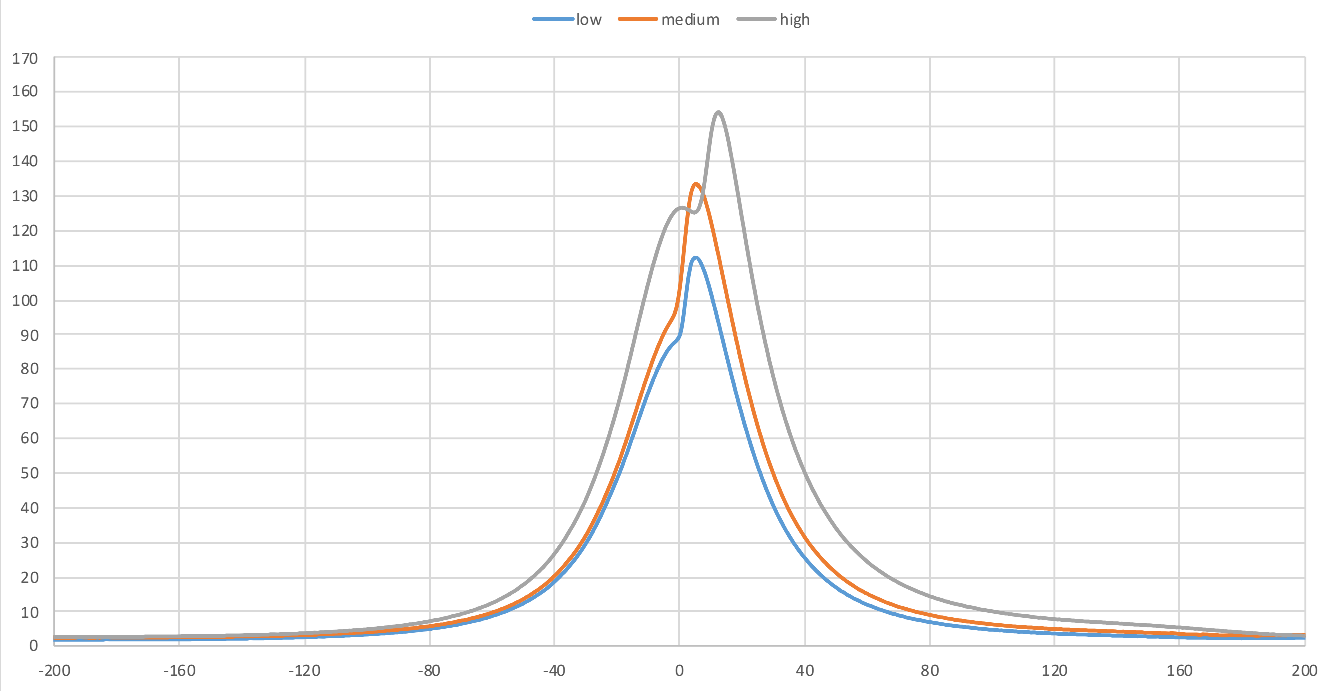
TCRCI Engine simulations

	low load		medium load		high load	
test	190827_p28		190913_p11		190723_p12	
GIMEP	4.4	bar	6.86	bar	13	bar
RPM	2000	1/min	2000	1/min	3000	1/min
m_inj_tot	13.5	mg	19	mg	35	mg
PFI	29.6	%	76.3	%	85.7	%
PFI_qty (gasoline)	4.00	mg	14.50	mg	30.00	mg
DI_qty (gasoline)	9.50	mg	4.50	mg	5.0	mg
split	0	%	0	%	0	%
DI_split1	0	mg	0	mg	0	mg
DI_split2	9.50	mg	4.50	mg	5.0	mg
SOI1	-	°CA bTDCF	-	°CA bTDCF	-	°CA bTDCF
SOI2	30	°CA bTDCF	32	°CA bTDCF	40	°CA bTDCF
Inj_time1	-	µs	-	µs	-	µs
Inj_time2	-	µs	-	µs	-	µs
T_fuelDI	390	°C	365	°C	360	°C
p_injDI	300	bar	300	bar	300	bar
EGR_ext	0	%	0	%	22	%
EGR_tot (ext+res)	7	%	6.7	%	25.4	%
O2 mass fraction	0.2293		0.2263		0.203	
N2 mass fraction	0.7674		0.7693		0.7668	
CO2 mass fraction	0.0024		0.0032		0.0219	
H2O mass fraction	0.0009		0.0012		0.0083	
p_IVC (-153°CA)	230000	Pa	240000	Pa	320000	Pa
T_IVC (-153°CA)	378	K	380	K	370	K
lambda	5.1		4.15		1.9	
lambda	4.7		3.5		2.1	
lambda_premix	17.230		5.439		2.217	
phi_premix	0.0580		0.1839		0.4511	

Cotellessa P., "Prototipazione e calibrazione sperimentale di un motore TCRCI", Master thesis in Mechanical Engineering, University of Modena and Reggio Emilia, March 2019

DI Injector geometry		
Inj_n_holes	6	
Spray angle	120	°
D_hole		

DI Injector geometry		
Inj_n_holes	6	
Spray angle	120	°
D_hole	0.219	mm



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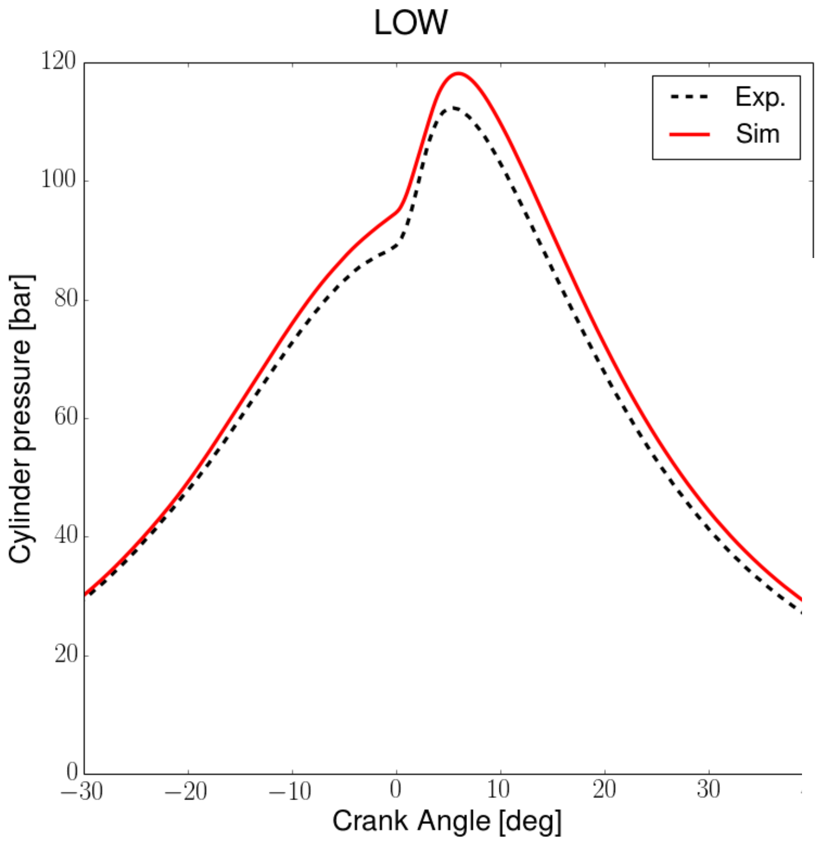
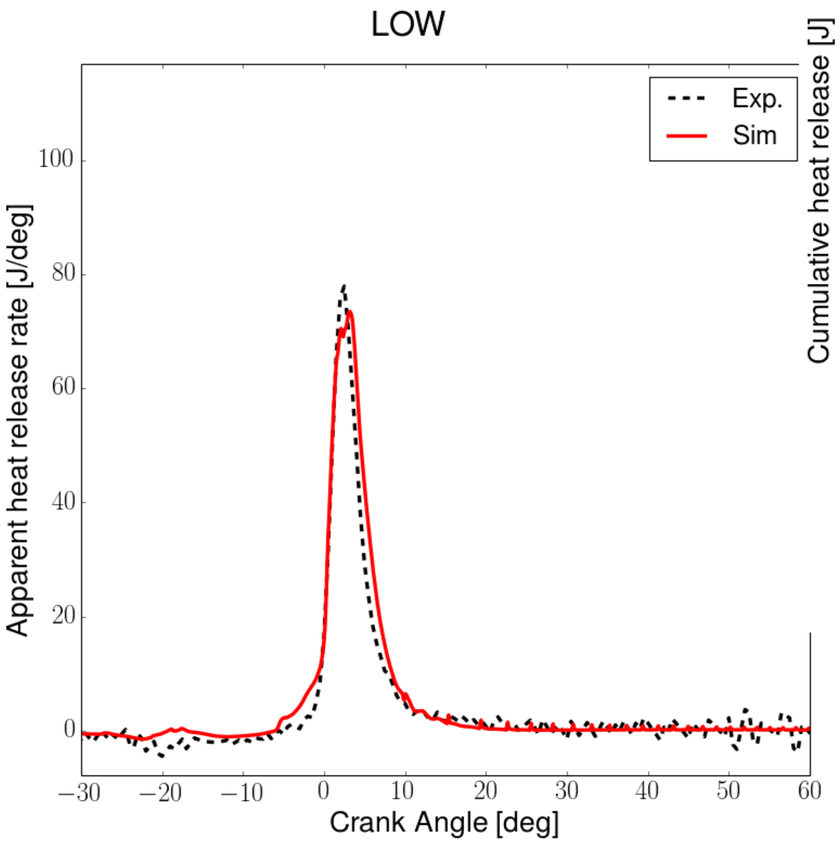
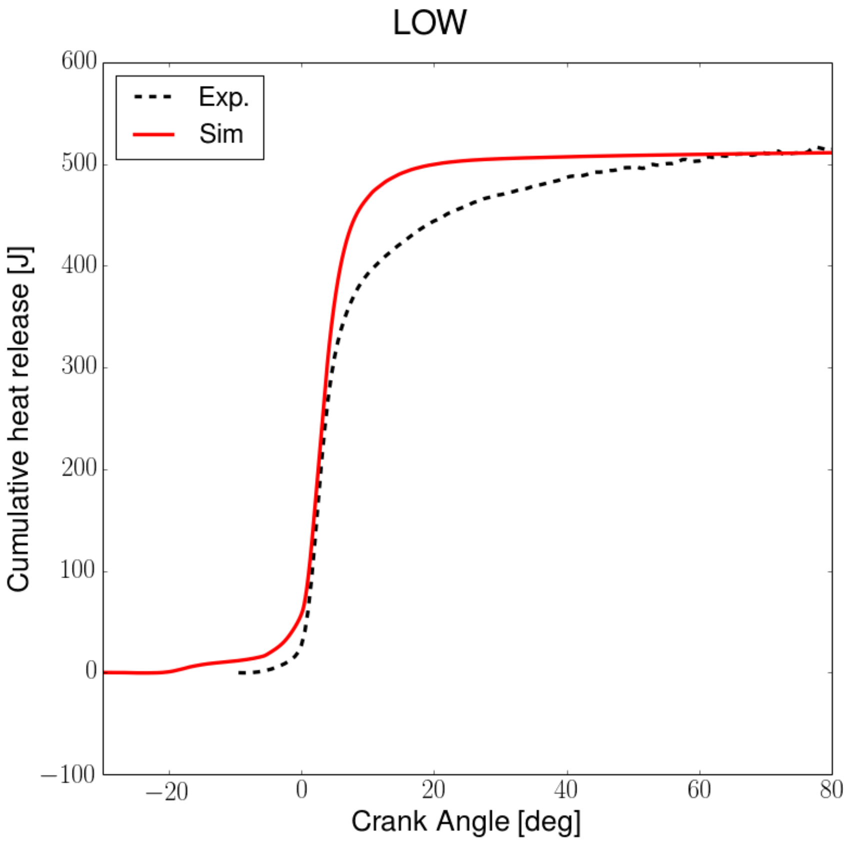
TCRCI Engine simulations: Low load







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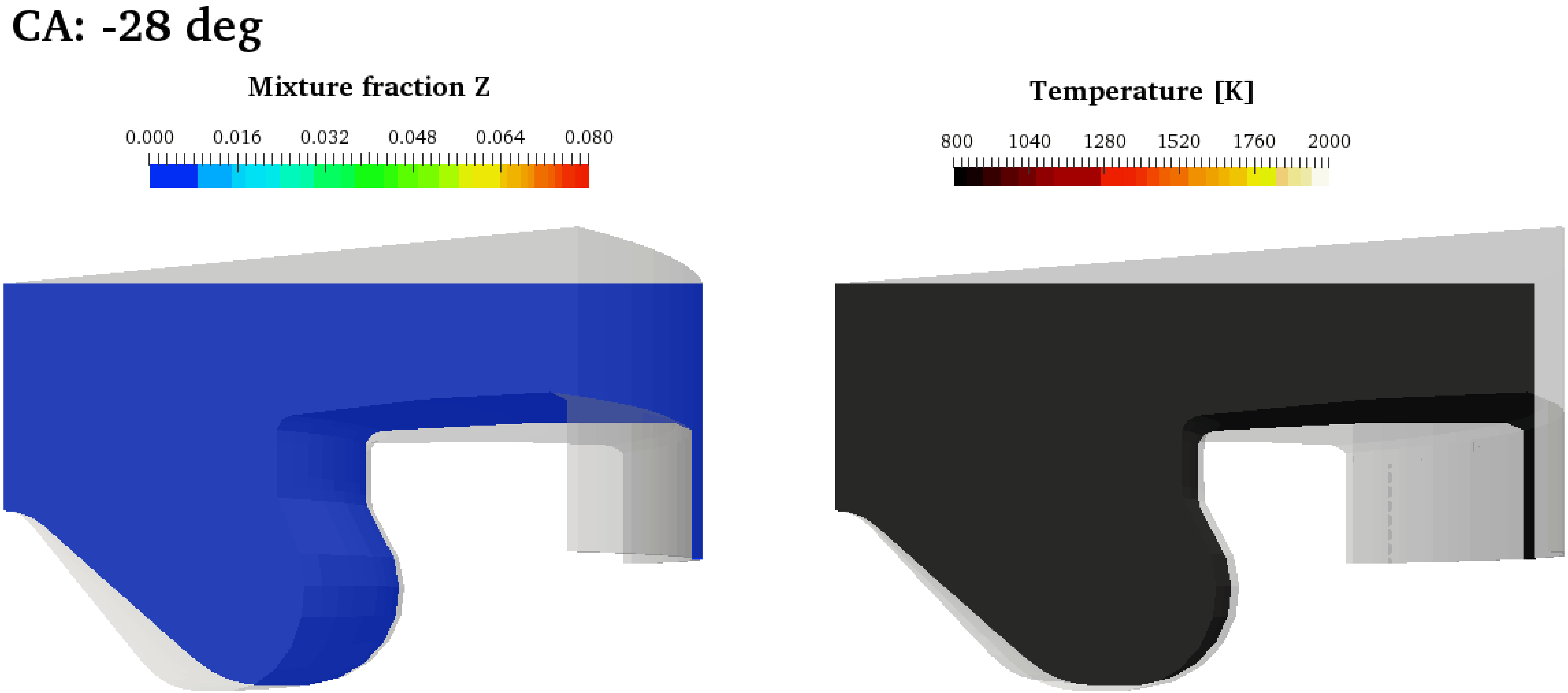
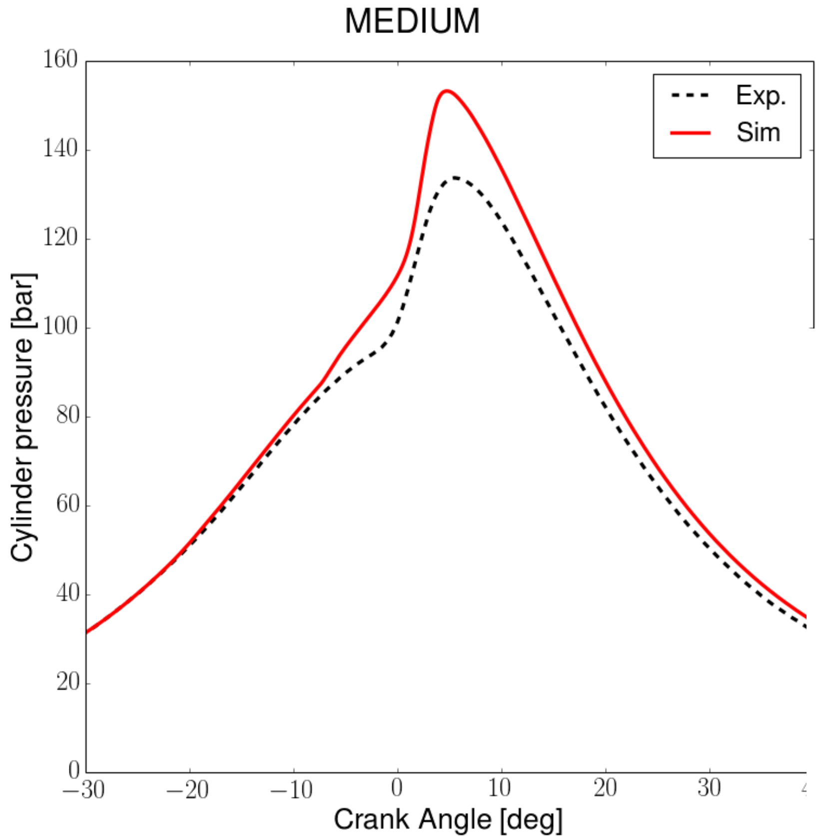
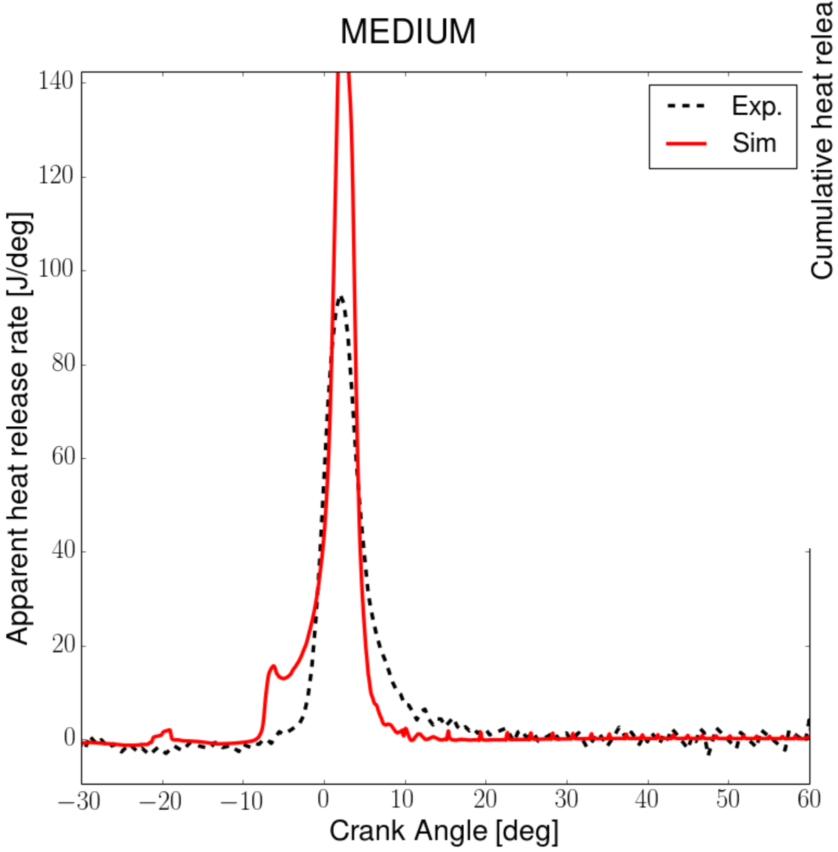
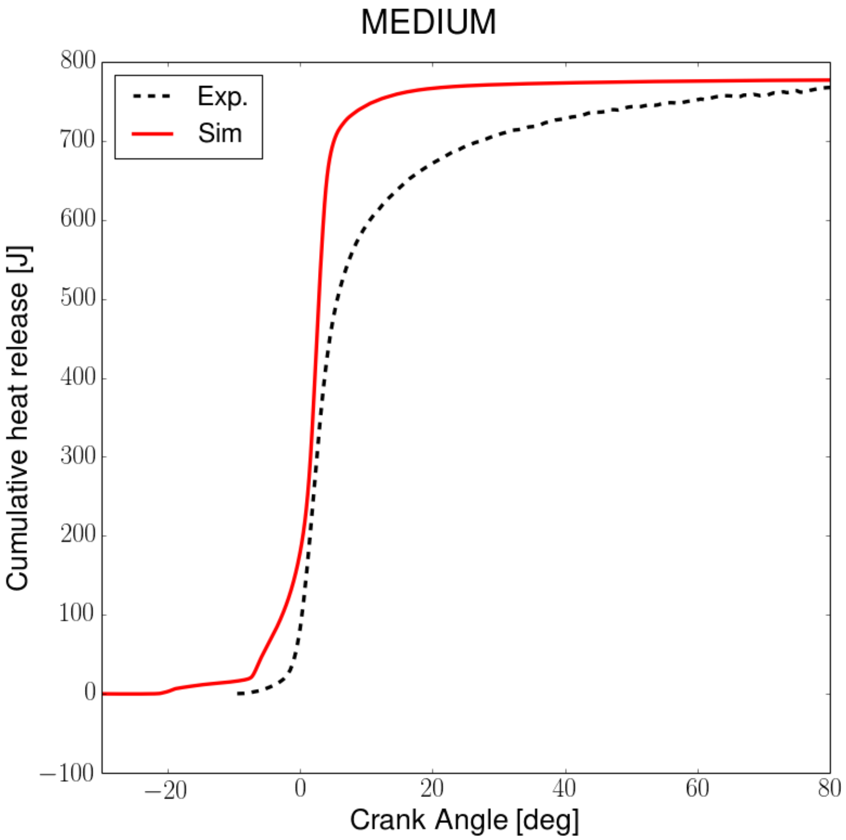
TCRCI Engine simulations: Low load



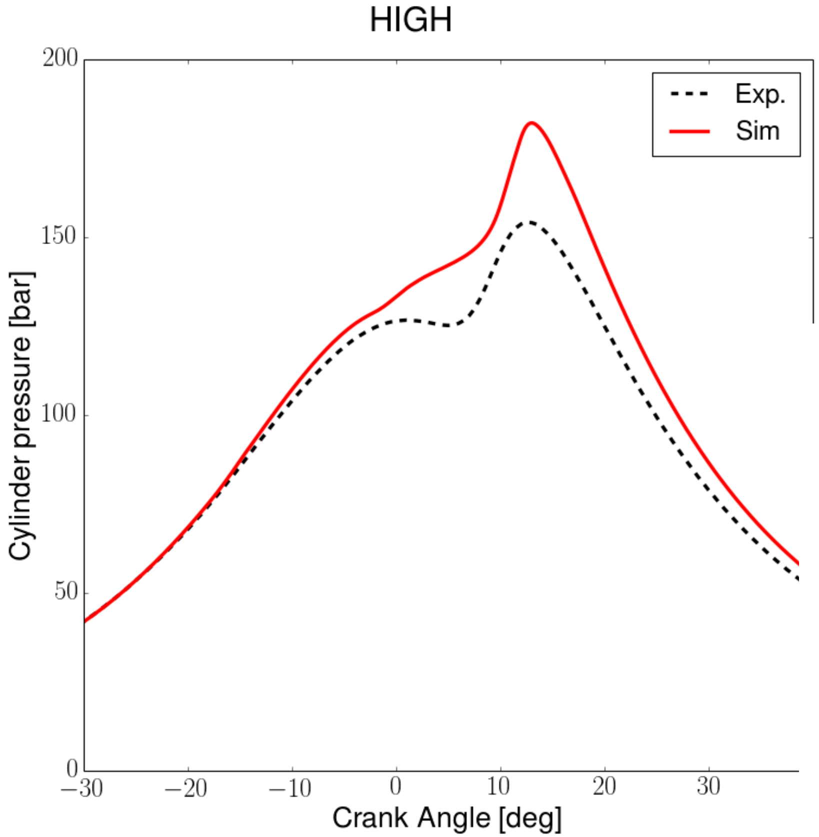
TCRCI Engine simulations: Medium load

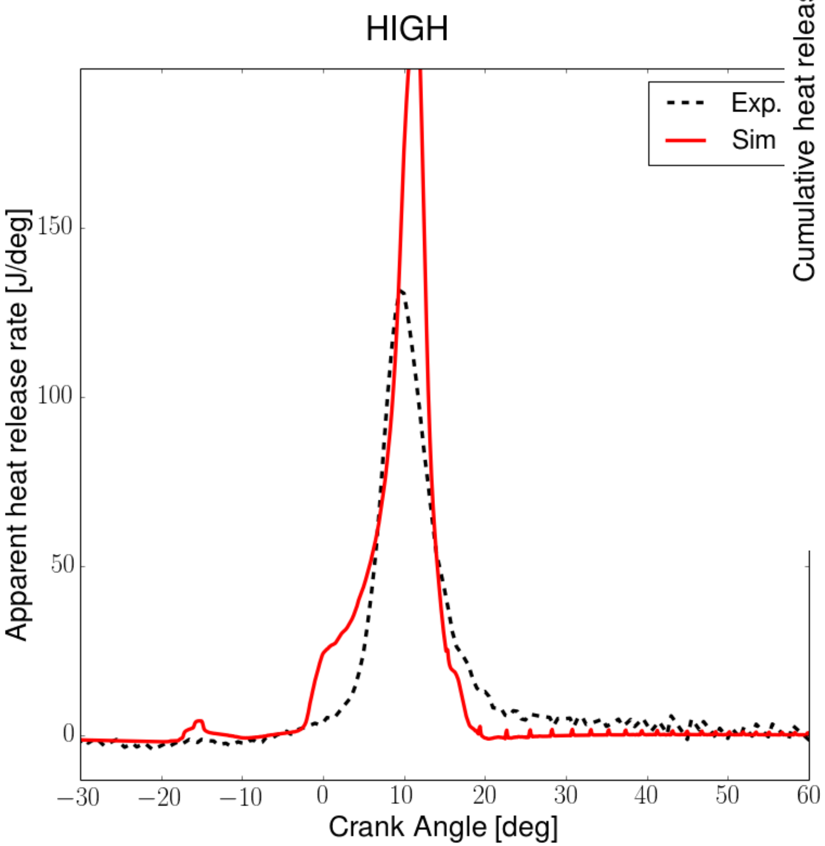


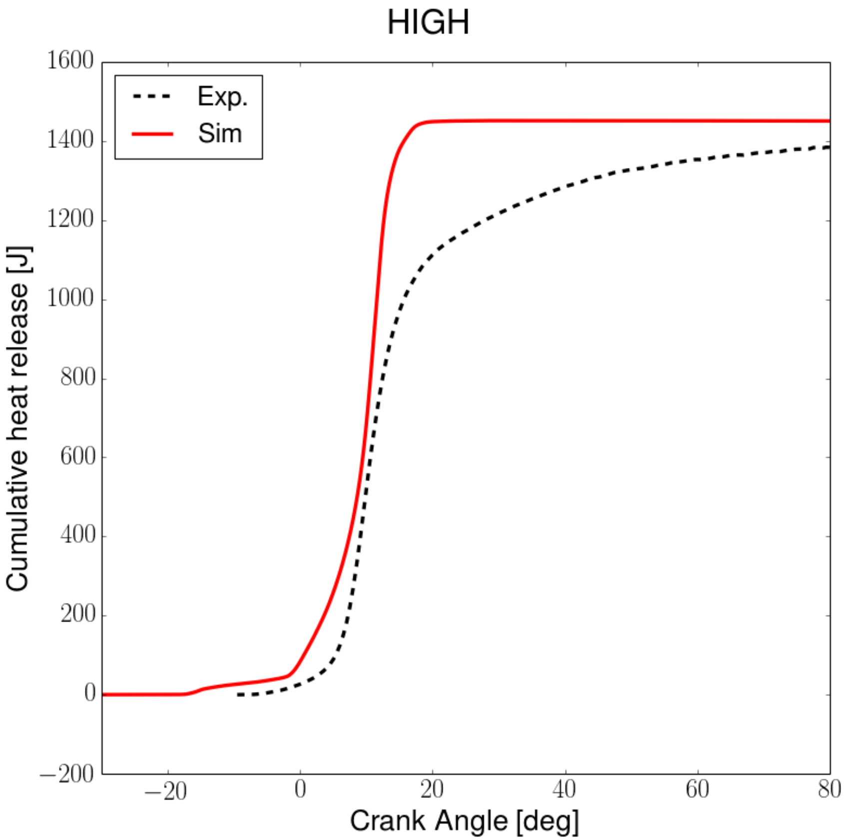




TCRCI Engine simulations: High load







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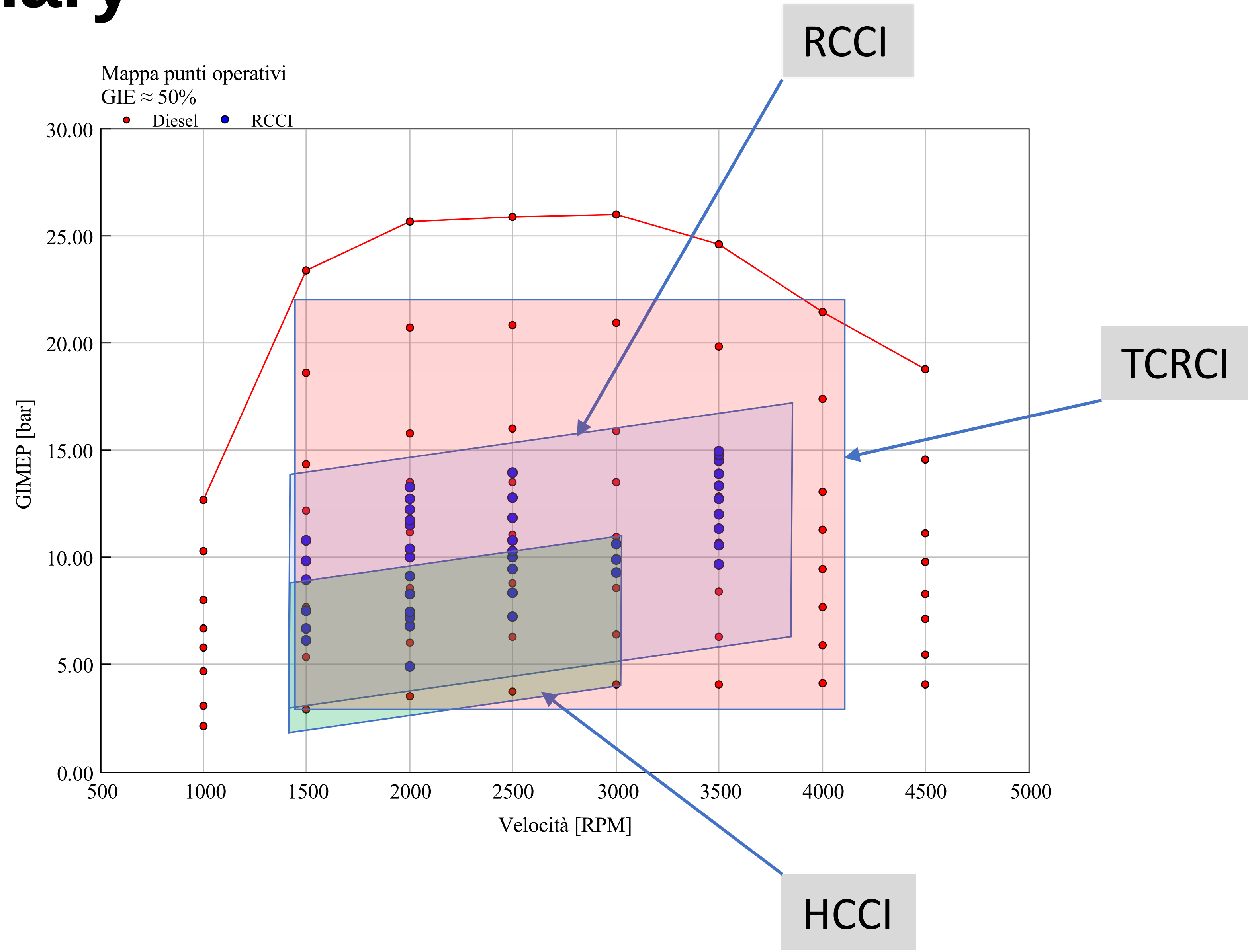
TCRCI results summary

- Use of a single gasoline-like fuel without any specific additive.
- Injection pressure levels comparable to current GDI technology (200-300 bar).
- Possibility to reach maximum engine load similar to RCCI and higher than HCCI (up to 15 bar IMEP).
- Potential to reach an IMEP of 20-25 bar with a better control of EGR.
- Better control with respect to HCCI (similar to RCCI).
- Possibility to use fuel with RON 98 without problem. In general it should be possible to use E-fuel and fuel with RON higher than 70 (tbc).
- Possibility to reach Indicated Efficiency close to 50% based on an existing diesel design.
- Possibility to reach Indicated Efficiency close to 55% with a bespoke design.
- Emission levels in terms of PM and NOx below Euro 6 standard without exhaust after treatment.
- HC and CO emission are high, but it needs to be tested a different piston bowl geometry

TCRCI results summary

- Mapping area with a Gross Indicated Efficiency close to 50 %
- Target map area for TCRCI (not reached yet)



Summary

Problem on correlation of lambda value to volumetric efficiency and exact amount of fuel.

- High load and high EGR critical for stability

Numerical simulation not accurate enough yet

- 1D model to be improved to correctly simulate residuals and scavenging during valve overlap.

Problem on keeping fuel injection temperature at a given value

- Redesign of injection system (adding thermal barrier inside and on the connections)
- Definition of a recirculation system before the injector to stabilise the inlet temperature.

Improvement on testing devices

- Possible introduction of a EGR pump (high pressure EGR not stable enough)
- Air flow meter
- Fuel flow meter in high pressure-high temperature line
- Experimental determination of Tfuel based on T at the inlet of injector

Thank you for the attention