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

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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\textsubscript{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

L. Marmorini
My background: motorsport, just motorsport.

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

Mazda Skyactive-X concept (SPCCI combustion)
Efficiency increase and emission control

- High-efficiency CI engines development
- Low-emissions
- 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

- Homogeneous Charge Compression Ignition (HCCI)
- Premixed Charge Compression Ignition (PCCI)
- Conventional Diesel Combustion (CDC)

In-cylinder fuel stratification at the SOC - Level of Heat Transfer losses

Level of soot/NOx – Combustion controllability

Efficiency – Level of CO and UHC
## Advanced combustion modes for direct-injection engines

<table>
<thead>
<tr>
<th>Mode</th>
<th>Ignition</th>
<th>Fuel 1</th>
<th>Fuel 2</th>
<th>Power cycle Efficiency</th>
<th>Emissions</th>
<th>Knock</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCCI</td>
<td>Direct</td>
<td>Diesel, biodiesel</td>
<td></td>
<td>~50%</td>
<td>HC and CO</td>
<td>YES</td>
</tr>
<tr>
<td>RCCI</td>
<td>Direct and PFI</td>
<td>Fuel 1: Diesel Fuel 2: Gasoline, CNG, ethanol</td>
<td></td>
<td>~55%</td>
<td>HC and CO</td>
<td>YES</td>
</tr>
<tr>
<td>SACI</td>
<td>Direct or PFI</td>
<td>Gasoline, CNG, ethanol</td>
<td></td>
<td>~50%</td>
<td>HC and CO</td>
<td>YES</td>
</tr>
</tbody>
</table>

**SA**: Spark Advance, **HR**: Heat Release, **R**: Percentage, **TDC**: Top Dead Center
RCCI Combustion concept

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

Disadvantages:
- High-performance turbo-machinery
- Optimization of combustion control strategies for different loads

Fuel chemical kinetics control

Fuel blending strategies

Control parameters
- Single-fuel
- Dual-fuel

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TCRCI Combustion concept

**RCCI strategy**
- Single-fuel
- Gasoline
- Hot GDI
- Heated fuel injection

**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

Control parameter: DI Fuel Temperature

Ignition

Combustion

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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

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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 from 350 to 500°C depending on engine speed and load.

The fuel heating can occur 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
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**

- **Mechanism**
  - \( Z \)
  - \( T_u \)
  - \( p \)
  - EGR

- **Table generator**

- **Homogeneous reactor**
  - \( \frac{dY_i}{dt} = \omega_i(Y_1, ..., Y_n, p, T) \)
  - \( T(t) = T(Y_i, h) \)
  - \( c(t) = c(Y_i, h) \)

- **Table**
  - \( \dot{c}(c), Y_{i,v}(c), Y_{i,o}(c) \)

- **Virtual species mass fractions**
  - \( Y_{v,i}(t) \)

CFD solver: tabulated kinetics ensures reduced computational time and results accuracy:
- **suitable tool to study and design engines with advanced combustion concepts.**

- **CFD solver**
  - \( \tilde{T}(x) \)
  - \( \tilde{h}(x) = \sum \tilde{Y}_i \cdot h_i \)

- **\( \tilde{Y}_i(Z, c, T_u, p) \)**

- **\( \tilde{Y}_o(Z, c, T_u, p) \)**

- **\( \dot{\omega}_c(Z, c, T_u, p) \)**

- **\( \tilde{Z}(x), \tilde{c}(x), \tilde{T}_u(x), \tilde{p}(x) \)**

- **Table**

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TCRCI assessment at constant volume conditions

- **Mesh**: 1/8 of the combustion chamber volume

- **Injection**

  - 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CDC Gasoline surrogate</th>
<th>TCRCI Gasoline surrogate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure [bar]</td>
<td>20-250 (step 30)</td>
<td></td>
</tr>
<tr>
<td>Temperature [K]</td>
<td>600-1300 (step 50)</td>
<td></td>
</tr>
<tr>
<td>Equivalence Ratio</td>
<td>0-3 (finer resolution close to ϕ=1)</td>
<td></td>
</tr>
</tbody>
</table>

**Ambient conditions**

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

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TCRCI assessment at constant volume conditions

RoHR

Ignition Delay

Heated injection benefits

GDI/PFI

Optimal condition

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TCRCI assessment at constant volume conditions

**CDC**

TCRCI

**PFI-0.5/GDI-0.1**

**PFI-0.05/GDI-0.55**

**HCCI**

- Similar ignition delay times
- Combustion controllability – In-cylinder fuel stratification at the SOC - Level of soot/NOx
- Ignition Dwell - Knocking conditions

Key:

- PFI/GDI fuel ratio optimization
- Heated injection

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Light-duty engine: combustion mode comparison

Simulation set-up

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

Injection

PCCI

- Fuel: n-C\textsubscript{7}H\textsubscript{16} Diesel surrogate
- Mechanism: Curran (159 species)

<table>
<thead>
<tr>
<th>n [rpm]</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMEP [bar]</td>
<td>5</td>
</tr>
<tr>
<td>p@IVC [bar]</td>
<td>1.3</td>
</tr>
<tr>
<td>T@IVC [K]</td>
<td>403.52</td>
</tr>
<tr>
<td>EGR</td>
<td>~40%</td>
</tr>
<tr>
<td>Equivalence Ratio</td>
<td>~0.8</td>
</tr>
</tbody>
</table>

RCCI/TCRCI/HCCI

- Fuel:
  - DI: n-C\textsubscript{7}H\textsubscript{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 |

<table>
<thead>
<tr>
<th>n [rpm]</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMEP [bar]</td>
<td>5</td>
</tr>
<tr>
<td>Pressure at IVC [bar]</td>
<td>1.3</td>
</tr>
<tr>
<td>Temperature at IVC [K]</td>
<td>403.52</td>
</tr>
<tr>
<td>EGR</td>
<td>0%</td>
</tr>
<tr>
<td>Equivalence Ratio</td>
<td>0-0.42</td>
</tr>
</tbody>
</table>
Light-duty engine: RCCI combustion evaluation

SOI at high temperature optimization + PFI/GDI fuel ratio optimization = GIE > 45%

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.30+0.05</td>
<td>0.1°</td>
<td>4.92E-05</td>
<td>0.3°</td>
<td>-35.1°</td>
<td>381,526</td>
<td>843</td>
<td>45.25%</td>
</tr>
<tr>
<td>0.30+0.05</td>
<td>1.55°</td>
<td>1.12E-06</td>
<td>1.665°</td>
<td>-30.1°</td>
<td>393,334</td>
<td>879</td>
<td>45.42%</td>
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<tr>
<td>0.30+0.05</td>
<td>2.8°</td>
<td>1.08E-06</td>
<td>3.085°</td>
<td>-25.1°</td>
<td>394,576</td>
<td>869</td>
<td>45.38%</td>
</tr>
<tr>
<td>0.26+0.09</td>
<td>-1.92°</td>
<td>1.6E-06</td>
<td>-1.92°</td>
<td>-30.1°</td>
<td>391,641</td>
<td>872</td>
<td>44.87%</td>
</tr>
</tbody>
</table>

MFB50 near TDC

Early and more controllable combustion

Cool flames

Validated

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%

Retarded but more controllable combustion

MFB50 HCCI-comparable

Cool flames

Heat Transfer losses

Best SOI

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Light-duty engine: comparison of combustion modes

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

Different fuels

Reactivity-controlled

Heated injection

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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.

Gross indicated efficiency [%]

<table>
<thead>
<tr>
<th></th>
<th>PCCI</th>
<th>HCCI</th>
<th>TCRCI</th>
<th>RCCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>37%</td>
<td>38%</td>
<td>39%</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>41%</td>
<td>42%</td>
<td>43%</td>
<td>44%</td>
</tr>
<tr>
<td></td>
<td>45%</td>
<td>46%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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%

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TCRCI Experiments

3+1 Engine (TCRCI Layout)
TCRCI vs RCCI Experiments

Gross indicated efficiency as function of the IMEPH

TCRCI experimental data

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RCCI Engine simulations

<table>
<thead>
<tr>
<th></th>
<th>low load</th>
<th>medium load</th>
<th>high load</th>
</tr>
</thead>
<tbody>
<tr>
<td>test</td>
<td>181018_p12</td>
<td>181024_p6</td>
<td>181017_p27</td>
</tr>
<tr>
<td>GIMEP</td>
<td>4.8 bar</td>
<td>8.8 bar</td>
<td>14.5 bar</td>
</tr>
<tr>
<td>RPM</td>
<td>2000 1/min</td>
<td>2000 1/min</td>
<td>3500 1/min</td>
</tr>
<tr>
<td>m_inj_tot</td>
<td>10 mg</td>
<td>20 mg</td>
<td>30 mg</td>
</tr>
<tr>
<td>split</td>
<td>20 %</td>
<td>30 %</td>
<td>0 %</td>
</tr>
<tr>
<td>PFI</td>
<td>70 %</td>
<td>92 %</td>
<td>82 %</td>
</tr>
<tr>
<td>PFI_qty (gasoline)</td>
<td>7 mg</td>
<td>18.4 mg</td>
<td>24.6 mg</td>
</tr>
<tr>
<td>Dl_qty (diesel)</td>
<td>3 mg</td>
<td>1.6 mg</td>
<td>5.4 mg</td>
</tr>
<tr>
<td>SOI1</td>
<td>62 °CABTDCF</td>
<td>75 °CABTDCF</td>
<td>- °CABTDCF</td>
</tr>
<tr>
<td>SOI2</td>
<td>42 °CABTDCF</td>
<td>55 °CABTDCF</td>
<td>35 °CABTDCF</td>
</tr>
<tr>
<td>lnj_time1</td>
<td>238 μs</td>
<td>230 μs</td>
<td>- μs</td>
</tr>
<tr>
<td>lnj_time2</td>
<td>311 μs</td>
<td>255 μs</td>
<td>356 μs</td>
</tr>
<tr>
<td>T_fuelDI</td>
<td>40 °C</td>
<td>42 °C</td>
<td>43 °C</td>
</tr>
<tr>
<td>p_Rail</td>
<td>1095 bar</td>
<td>1210 bar</td>
<td>1600 bar</td>
</tr>
<tr>
<td>EGR_ext</td>
<td>0 %</td>
<td>25 %</td>
<td>38 %</td>
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<tr>
<td>EGR_tot (ext+res)</td>
<td>8.3 %</td>
<td>28 %</td>
<td>41 %</td>
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<tr>
<td>O2 mass fraction</td>
<td>0.2261</td>
<td>0.1968</td>
<td>0.1783</td>
</tr>
<tr>
<td>N2 mass fraction</td>
<td>0.7685</td>
<td>0.7659</td>
<td>0.7612</td>
</tr>
<tr>
<td>CO2 mass fraction</td>
<td>0.0039</td>
<td>0.027</td>
<td>0.0438</td>
</tr>
<tr>
<td>H2O mass fraction</td>
<td>0.0015</td>
<td>0.0103</td>
<td>0.0167</td>
</tr>
<tr>
<td>p_IVC (-153°C)</td>
<td>170000 Pa</td>
<td>170000 Pa</td>
<td>310000 Pa</td>
</tr>
<tr>
<td>T_IVC (-153°C)</td>
<td>350 K</td>
<td>355 K</td>
<td>380 K</td>
</tr>
<tr>
<td>lambda</td>
<td>2.885</td>
<td>1.374</td>
<td>1.057</td>
</tr>
<tr>
<td>lambda</td>
<td>5.2</td>
<td>2.1</td>
<td>1.9</td>
</tr>
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<td>lambdaPremix</td>
<td>4.121</td>
<td>1.493</td>
<td>1.289</td>
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<tr>
<td>phi_Premix</td>
<td>0.2426</td>
<td>0.6696</td>
<td>0.7758</td>
</tr>
</tbody>
</table>

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

CA: -58 deg

Mixture fraction $Z$

Temperature [K]

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RCCI Engine simulations: Medium load
RCCI Engine simulations: High load

**Cylinder pressure [bar]**

- **Exp.**
- **Sim**

**Crank Angle [deg]**

**Apparent heat release rate [J/deg]**

**Cumulative heat release [J]**

**Crank Angle [deg]**

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RCCI Engine simulations: results summary
TCRCI Engine simulations

<table>
<thead>
<tr>
<th>test</th>
<th>low load</th>
<th>medium load</th>
<th>high load</th>
</tr>
</thead>
<tbody>
<tr>
<td>GIMEP</td>
<td>4.4 bar</td>
<td>6.86 bar</td>
<td>13 bar</td>
</tr>
<tr>
<td>RPM</td>
<td>2000 1/min</td>
<td>2000 1/min</td>
<td>3000 1/min</td>
</tr>
<tr>
<td>( \text{m}_{\text{inj tot}} )</td>
<td>13.5 mg</td>
<td>19 mg</td>
<td>35 mg</td>
</tr>
<tr>
<td>PFI</td>
<td>29.6 %</td>
<td>76.3 %</td>
<td>85.7 %</td>
</tr>
<tr>
<td>PFI (_{\text{qty}}) (gasoline)</td>
<td>4.00 mg</td>
<td>14.50 mg</td>
<td>30.00 mg</td>
</tr>
<tr>
<td>( \text{D}_{\text{lqty}} ) (gasoline)</td>
<td>9.50 mg</td>
<td>4.50 mg</td>
<td>5.0 mg</td>
</tr>
<tr>
<td>split</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>( \text{D}_{\text{split1}} )</td>
<td>0 mg</td>
<td>0 mg</td>
<td>0 mg</td>
</tr>
<tr>
<td>( \text{D}_{\text{split2}} )</td>
<td>9.50 mg</td>
<td>4.50 mg</td>
<td>5.0 mg</td>
</tr>
<tr>
<td>SOI1</td>
<td>30 °C</td>
<td>365 °C</td>
<td>360 °C</td>
</tr>
<tr>
<td>SOI2</td>
<td>30 °C</td>
<td>32 °C</td>
<td>40 °C</td>
</tr>
<tr>
<td>Inj(_{\text{time1}})</td>
<td>-( \mu )s</td>
<td>-( \mu )s</td>
<td>-( \mu )s</td>
</tr>
<tr>
<td>Inj(_{\text{time2}})</td>
<td>-( \mu )s</td>
<td>-( \mu )s</td>
<td>-( \mu )s</td>
</tr>
<tr>
<td>T(_{\text{fuelDi}})</td>
<td>300 bar</td>
<td>300 bar</td>
<td>300 bar</td>
</tr>
<tr>
<td>( \text{p}_{\text{injDi}} )</td>
<td>0 %</td>
<td>0 %</td>
<td>22 %</td>
</tr>
<tr>
<td>EGR(_{\text{ext}})</td>
<td>7 %</td>
<td>6.7 %</td>
<td>25.4 %</td>
</tr>
<tr>
<td>O2 mass fraction</td>
<td>0.2293</td>
<td>0.2263</td>
<td>0.203</td>
</tr>
<tr>
<td>N2 mass fraction</td>
<td>0.7674</td>
<td>0.7693</td>
<td>0.7668</td>
</tr>
<tr>
<td>CO2 mass fraction</td>
<td>0.0024</td>
<td>0.0032</td>
<td>0.0019</td>
</tr>
<tr>
<td>H2O mass fraction</td>
<td>0.0009</td>
<td>0.0012</td>
<td>0.0083</td>
</tr>
<tr>
<td>( \text{p}_{\text{IWC}}) (-153°C)</td>
<td>230000 Pa</td>
<td>240000 Pa</td>
<td>320000 Pa</td>
</tr>
<tr>
<td>T(_{\text{IWC}}) (-153°C)</td>
<td>378 K</td>
<td>380 K</td>
<td>370 K</td>
</tr>
<tr>
<td>lambda</td>
<td>5.1</td>
<td>4.15</td>
<td>1.9</td>
</tr>
<tr>
<td>lambda</td>
<td>4.7</td>
<td>3.5</td>
<td>2.1</td>
</tr>
<tr>
<td>lambda (_{\text{premix}})</td>
<td>17.230</td>
<td>5.439</td>
<td>2.217</td>
</tr>
<tr>
<td>phi(_{\text{premix}})</td>
<td>0.0580</td>
<td>0.1839</td>
<td>0.4511</td>
</tr>
</tbody>
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Cotellessa P., "Prototipazione e calibrazione sperimentale di un motore TCRCI", Master thesis in Mechanical Engineering, University of Modena and Reggio Emilia, March 2019

L. Marmorini
TCRCI Engine simulations: Low load

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TCRCI Engine simulations: Low load

CA: -28 deg

Mixture fraction $Z$

Temperature [K]
TCRCI Engine simulations: Medium load

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TCRCI Engine simulations: High load

- Cylinder pressure [bar]
- Apparent heat release rate [J/deg]
- Cumulative heat release [J]

Crank Angle [deg]
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 $T_{\text{fuel}}$ based on $T$ at the inlet of injector
Thank you for the attention