Tailoring Gasoline Reactivity Through Ozone Seeding for LTC Compression Ignition Engine

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❑ Background

Suitable LTC concepts aim to simultaneously increase internal combustion engine efficiency and drastically decrease pollutant emissions without costly hardware additions

LTC Engine with current and future constraints:

- Fuels: Standard Gasoline grade fuel / gaseous fuels (natural gas, hydrogen), biofuels- gasoline blends

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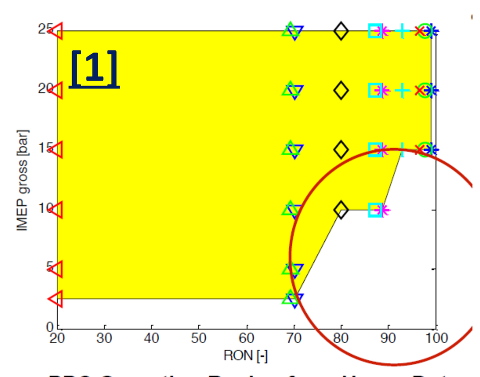


PPC Operating Region from Heavy Duty Experiments [1]

Advantage :
- High Efficiency due to elevated compression ratios
- Low emissions (NOx and Soot)

Drawbacks:
- Poor low load stability
- Challenging cold start, warm-up…

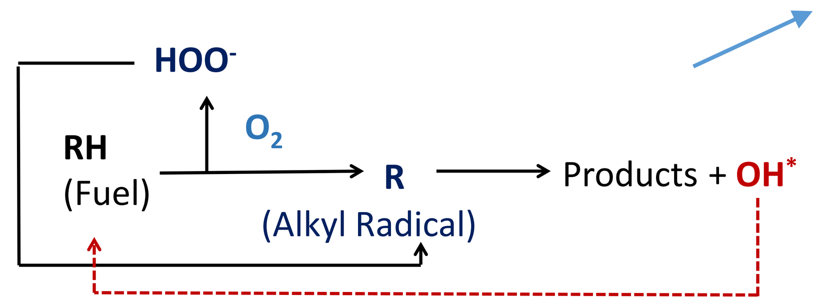
Solutions:
- Igniter, Octane on the demand, Reactivity of the air on the demand → Ozone – Air – Fuel reaction

Ozone: Promising Combustion Promoter [2]

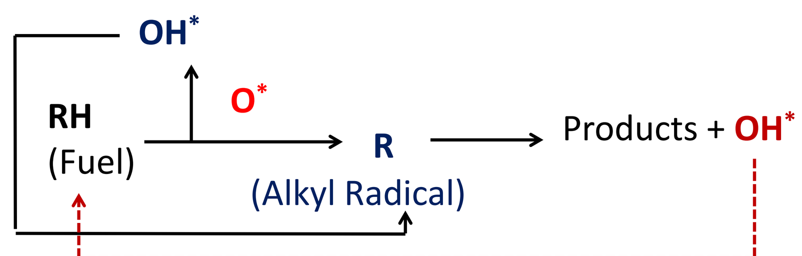
- Ozone Decomposition

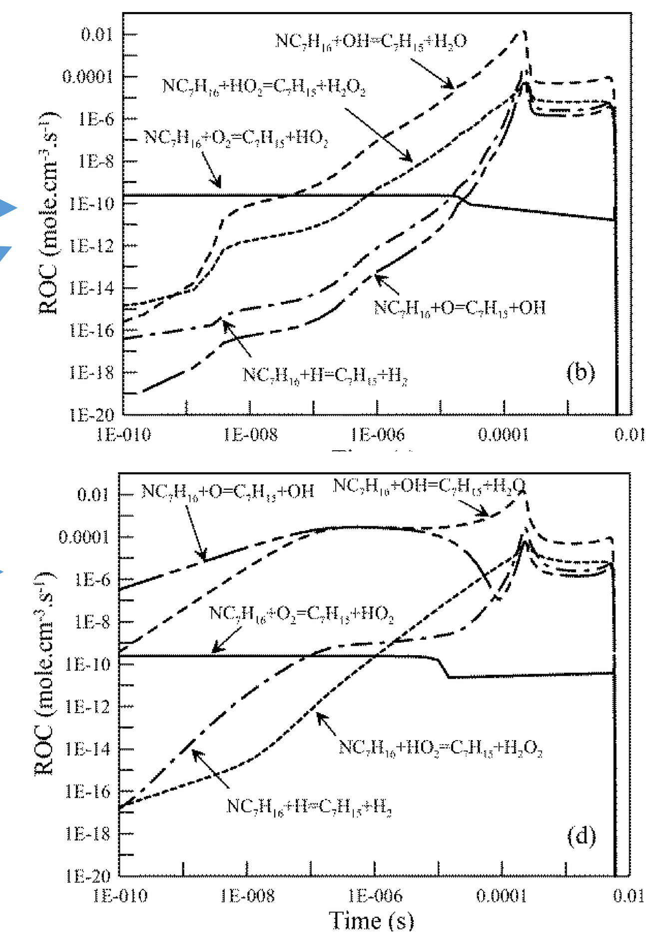
$O_3 \longrightarrow O_2 + O^*$

- Neat Fuel Oxidation



- Ozone-seeded Fuel Oxidation [4]

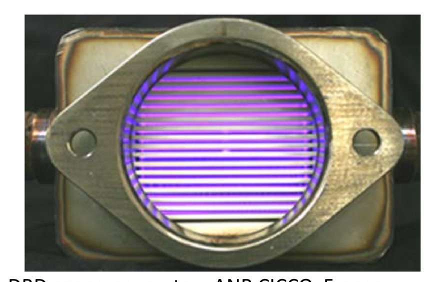




Ozone assisted LTC combustion enables tailored heat release rates for each cycle [3, 4]

Dedicated intake port ozonator:
(like SkyActiv-X Mazda engine !?)

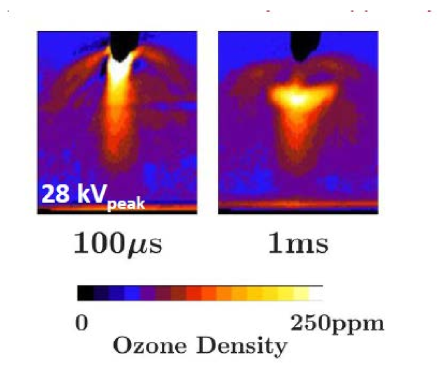
⇨ DBD Discharge
sinusoid or nanosecond High Voltage



Prototype DBD ozone generator, ANR CICCO, France

Advanced plasma igniters that generate early-cycle, in-cylinder ozone:

⇨ Corona, nanopulse Discharge …

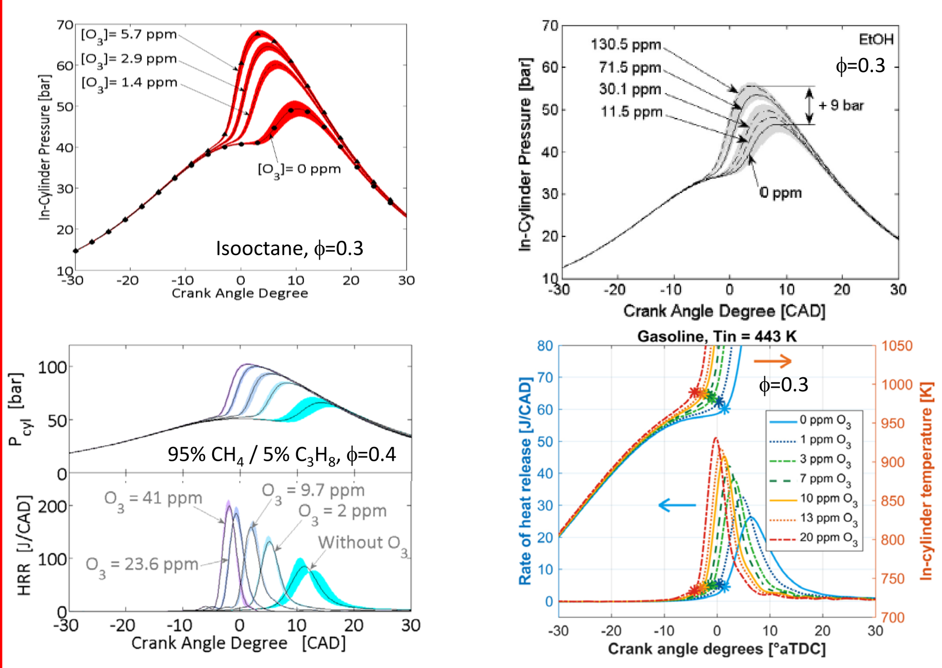


Ono & Oda, J. Phys. D: Appl. Phys., 2007

❑ Main Results

(1) Ozone improves the reactivity of many fuels [5-9]

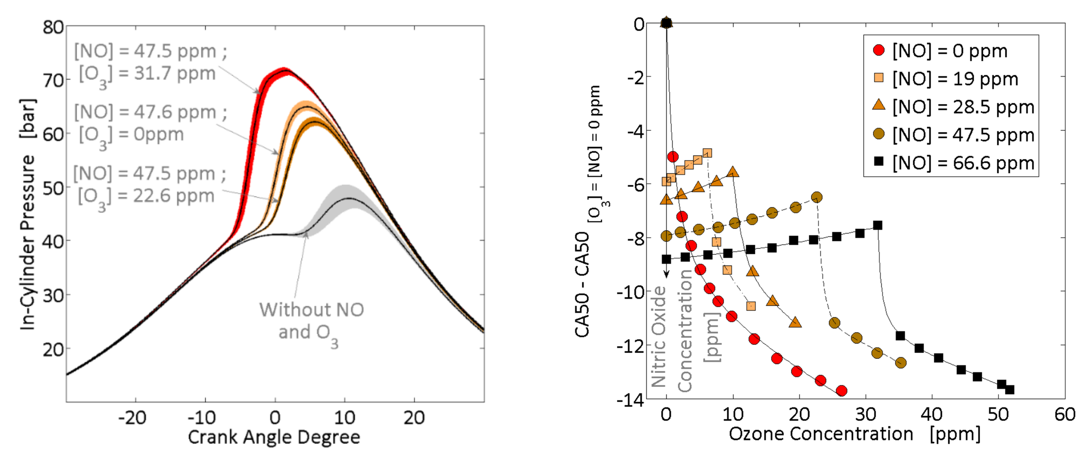
❑ Impact of ozone addition evaluated as function of fuel-type for HCCI combustion



(2) Ozone interactions with residual species during the compression stroke need to be accounted for [10]

❑ Ozone and NOx (from residual or recirculated gas) can interact and decrease the oxidation potential of ozone

❑ NO and NO_2 likewise influece fuel reactivity, but to a lesser extent.



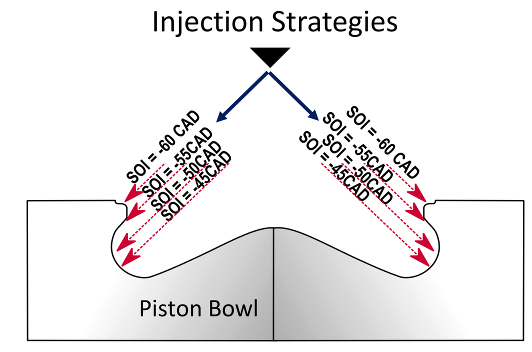
reaction between both oxidizing species $NO + O_3 \rightarrow NO_2 + O_2$

(3) The fuel injection strategy can lead to NO generation, which decreases the impact of ozone Addition [11, 12]

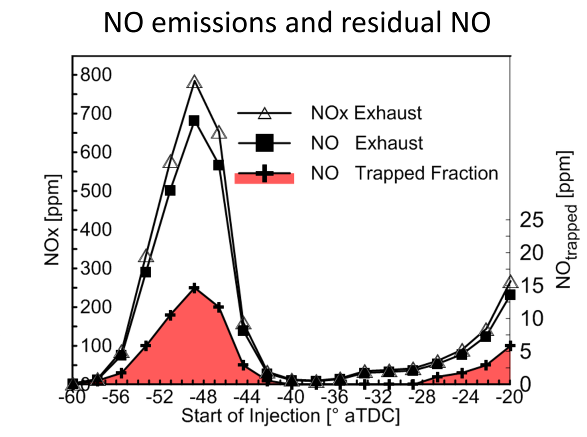
❑ With late-cycle direct injection, NOx emission is linked to the spray bowl interaction.

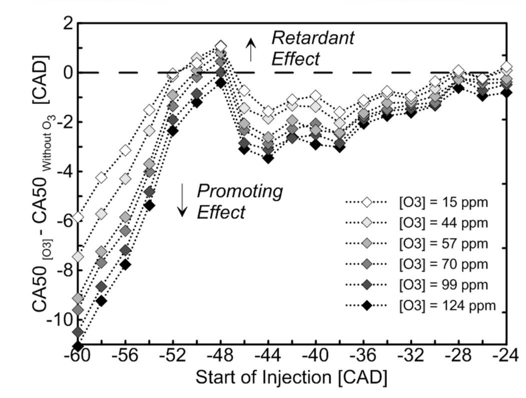
❑ Ozone does not have a monotonic influence on the ignition delay

Injection Strategies



NO emissions and residual NO





Ozone and NO have a strong chemical Affinity

❑ $NO_{trapped}$ reacts with ozone in GCI operation

❑ $NO_{trapped}$ is transformed in NO_2

$NO + O_3 \rightarrow NO_2 + O_2$

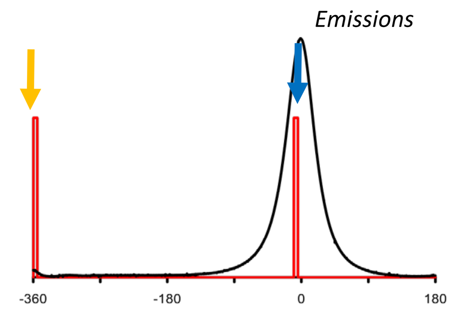
(4) Ozone Assisted LTC: Injection strategy and combustion control at low-loads [12]

❑ Ozone rapidly decomposes into O+O_2 during the compression stroke

❑ Late-cycle SOI needs to appropriately timed to take advantage of ozone decomposition to maximize the ozone-fuel interactions

1st Early Injection
Catch O_3 effect

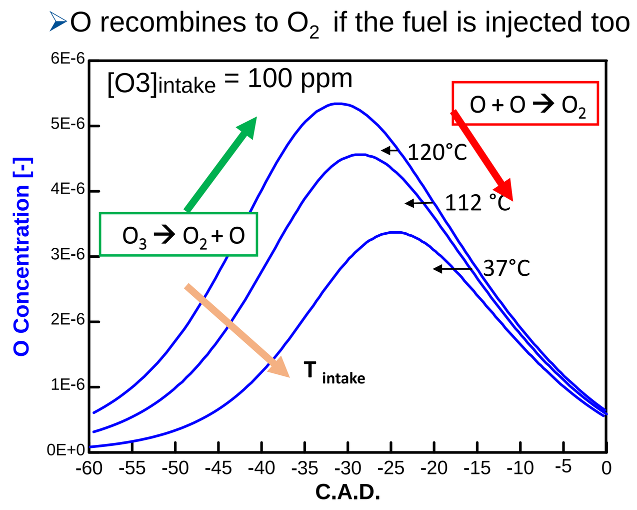
2nd Injection
Control CA50 –Noise - Emissions



❑ Senkin simulations for motored conditions

➢O availability varies during compression stroke

➢O recombines to O_2 if the fuel is injected too late

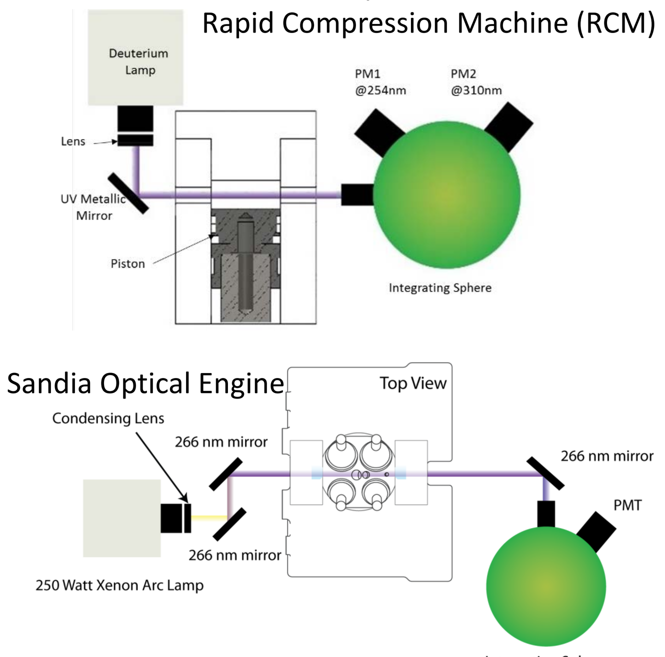


(5) Ozone kinetic mechanisms, and the associated fuel and EGR interactions [13]

❑ O_3 kinetics are not well known at high pressure/temperature conditions

❑ Current O_3 mechanisms lack accurate fuel/EGR interactions

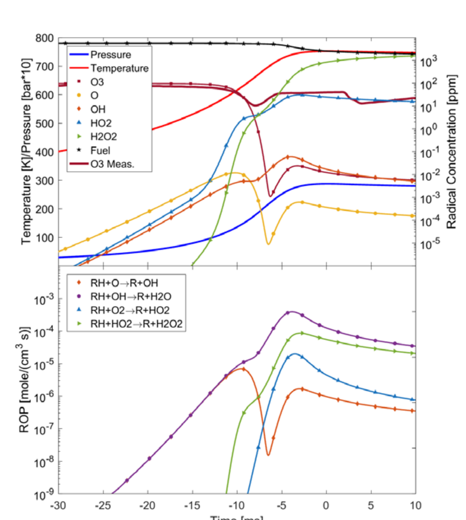
U. Orléans Optical Rapid Compression Machine (RCM)



Decomposition
1. $O_3 + O_2 \leftrightarrow O_2 + O + O_2$
2. $O_3 + N_2 \leftrightarrow O_2 + O + N_2$
3. $O_3 + O_3 \leftrightarrow O_2 + O + O_3$

Fuel Interactions
4. $O_3 + CH_3 \leftrightarrow O_2 + CH_3O$
5. $O_3 + CH_4 \leftrightarrow HO_2 + CH_3O$

Fuel Oxidation
6. $RH + O \rightarrow R + OH$
7. $RH + OH \rightarrow R + H_2O$
8. $RH + O_2 \rightarrow R + HO_2$
6. $RH + HO_2 \rightarrow R + H_2O_2$

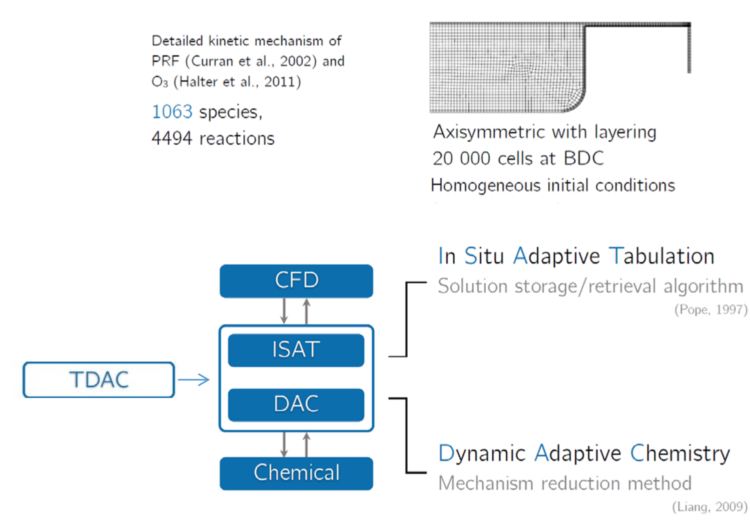


(6) CFD Simulation of an HCCI engine (Openfoam) [14]

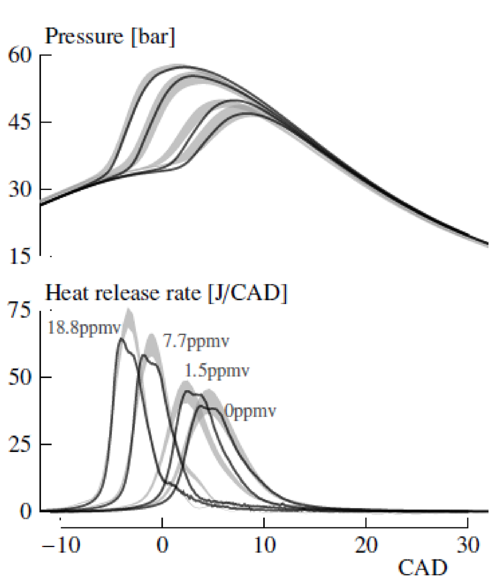
❑ Minor species (O_3, NO, NO_2…) need to be taken into account

❑ Tabulation of many species or large mechanism with dynamic chemical mechanism reduction is under consideration

CFD simulation performed on a axisymmetric mesh with a mechanism of 1000+ species



Isooctane, ϕ=0.3



Perspectives and Future Work

- ❑ Use single-cylinder research engines to improve the understanding of different concepts
- ❑ Apply non-intrusive optical diagnostics to better understanding the physical and chemical mechanisms
  - ❑ Measure ozone destruction during the compression stroke
  - ❑ Improve the understanding of the local ignition
  - ❑ Characterize the discharge and the production of the key species
- ❑ Improve current ozone kinetics mechanisms
  - ❑ Benchmark the prediction of O_3 decomposition and O formation during the compression stroke
  - ❑ Include minor species concentration effects (O_3, O, NO, NO_2…) into skeletal CFD O_3 kinetics mechanisms
- ❑ Optimize O_3 production from plasma discharges:
  - ❑ Energy balance as function of ozone production
  - ❑ Evaluate impact of ozone production on dominant in-cylinder gas constituents (Air, H_2O, CO_2, N_2…)
  - ❑ Characterize the impact of minor species produced by the plasma discharge
  - ❑ Evaluate the ability of ozone control during engine transients
- ❑ Measure auto-ignition delays of air-diluent-fuel-ozone mixture s in a RCM
  - ❑ Perform simultaneous measurements of ozone decomposition

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