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Spark Assisted Compression Ignition Engine with Stratified Charge Combustion and Ozone Addition

Paper # 20199089

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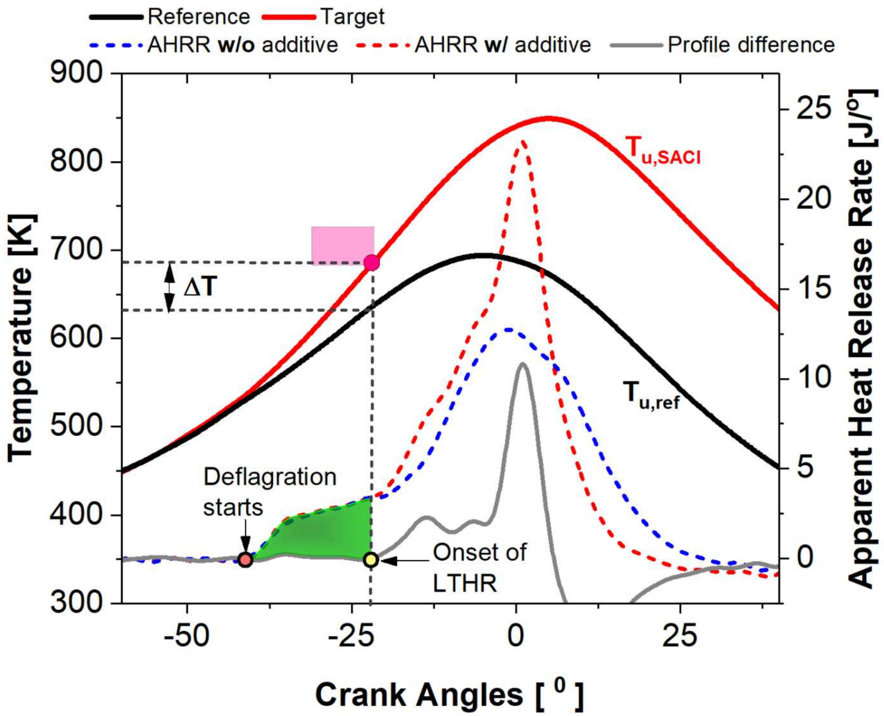
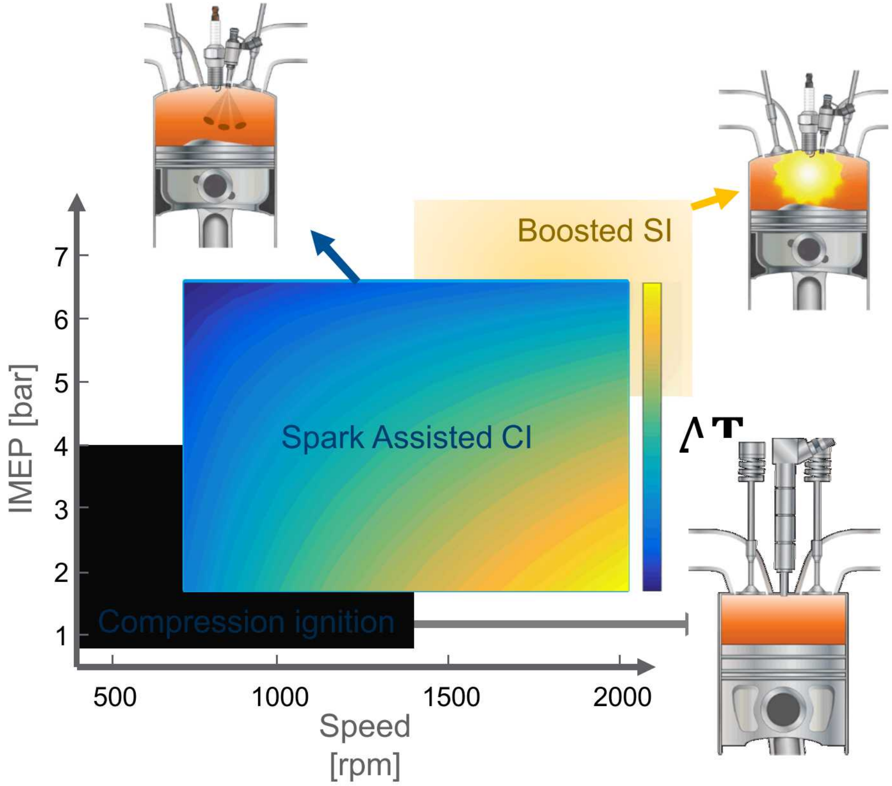
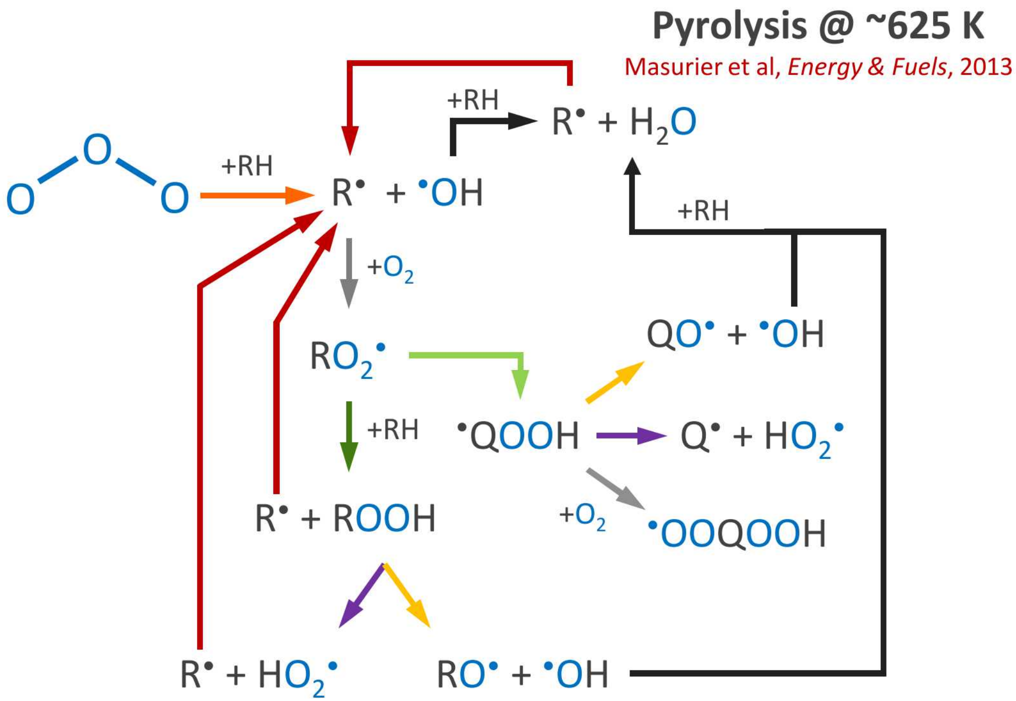
Multi-mode combustion strategies can be beneficial for high-efficiency and reduced emission





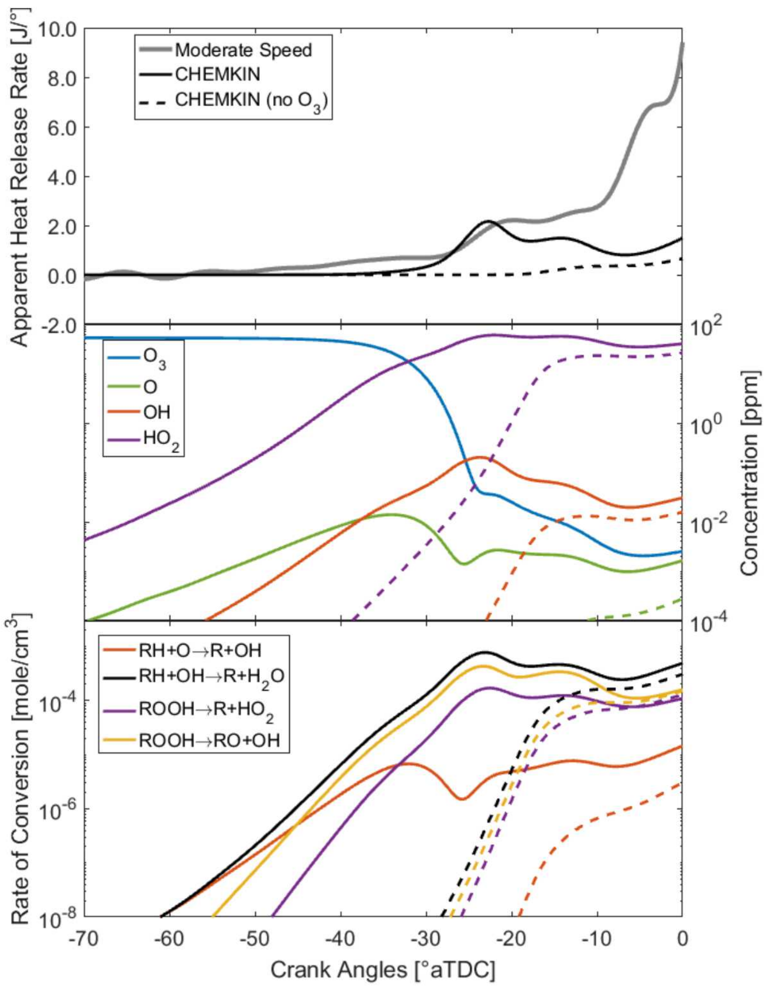
Advanced ignition can enable O_3 enhanced assisted compression ignition (SACI) (likewise benefits dilute/lean SI & enables spark retard for boosted SI)

Ozone addition enables low-temperature heat release (LTHR)



O_3 impact on LTHR Chemical Pathways

- O_3 pyrolysis depends on temperature & composition
- Fuel hydrogen abstraction by atomic oxygen (O•)
- Chain branching reactions form more alkyl radical (R•) and hydroxyl (OH•)



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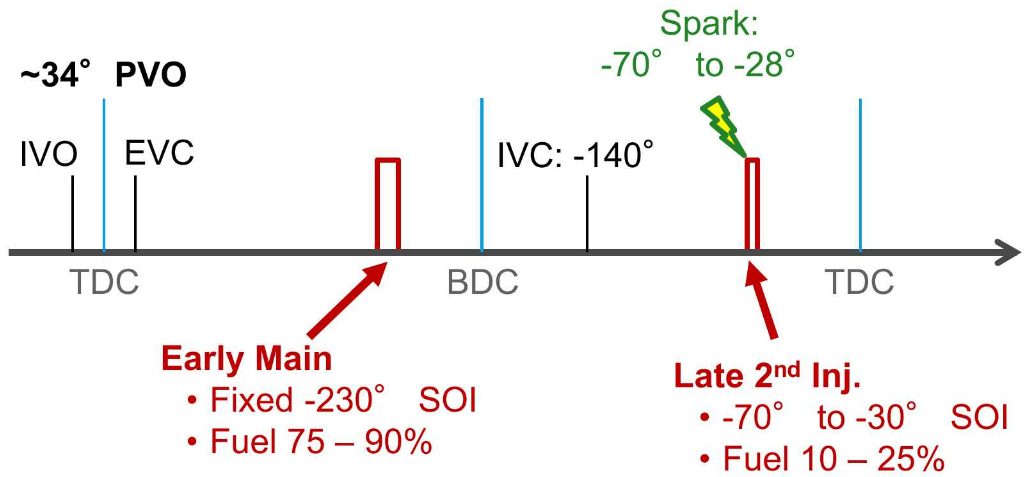
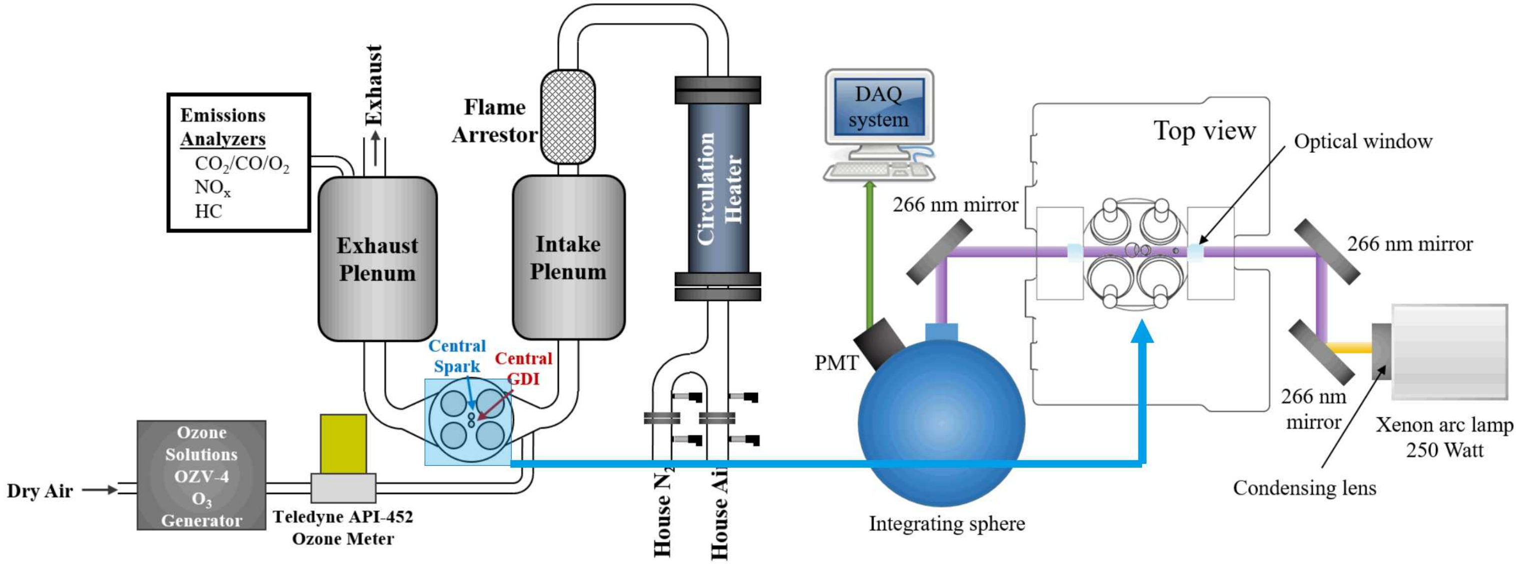
Hardware and operating strategy

Combustion Mode	Spark Assisted CI
Head Design	4-valve pent-roof
Injector	Central VCO, 8 holes
Displaced volume [L]	0.55
Stroke/Bore	1.11
Compression Ratio	13:1
Intake Pressure [bar]	1
Intake Temperature [°C]	42
Intake O_3 Conc. [ppm]	0 – 34
Engine Speed [rpm]	800, 1000, 1200, 1400, 1600
Equivalence ratio	0.27 – 0.56
RGF [%]	10 – 18
2nd injection [%]	0 – 25

Partially stratified strategy

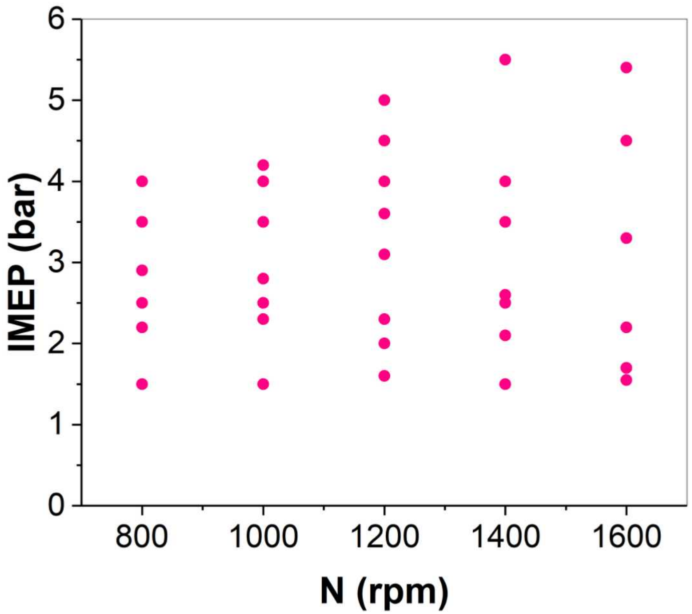




$$X_{O_3} = \frac{p_{O_3}}{p} = \ln\left(\frac{I_{ref}}{I}\right)\frac{k_B T}{p B \sigma_{O_3}}$$

k_B: Boltzmann constant
σ_{O_3}: O_3 absorption cross-section
B: Bore diameter
T: Bulk temperature
p: Total pressure
I, I_{ref}: Intensity

Operating points and optimization strategy



For N rpm, P IMEP

Constraint 1 — • Indicated thermal efficiency ↑

Constraint 2 — • NOx ↓ (< 5 g/kg-fuel)

Constraint 3 — • Ringing intensity ↓ (< 1 MW/m^2)

For a fixed O_3 concentration iterate for

- Fuel split, $m_{f\ 2nd\ inj.}$ — • **< 25% in 2nd inj.**
- Spark timing — • **70^0 – 28^0 bTDC**
- 2nd inj. SOI — • **64^0 – 36^0 bTDC**

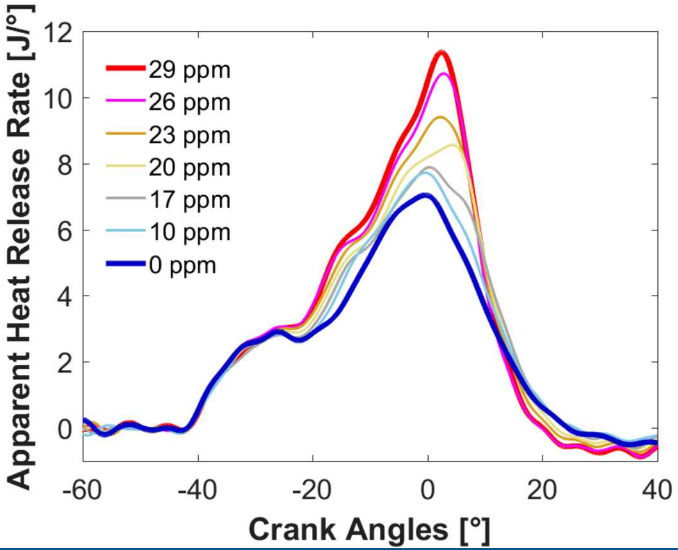
Optimize for maximum brake torque (MBT)

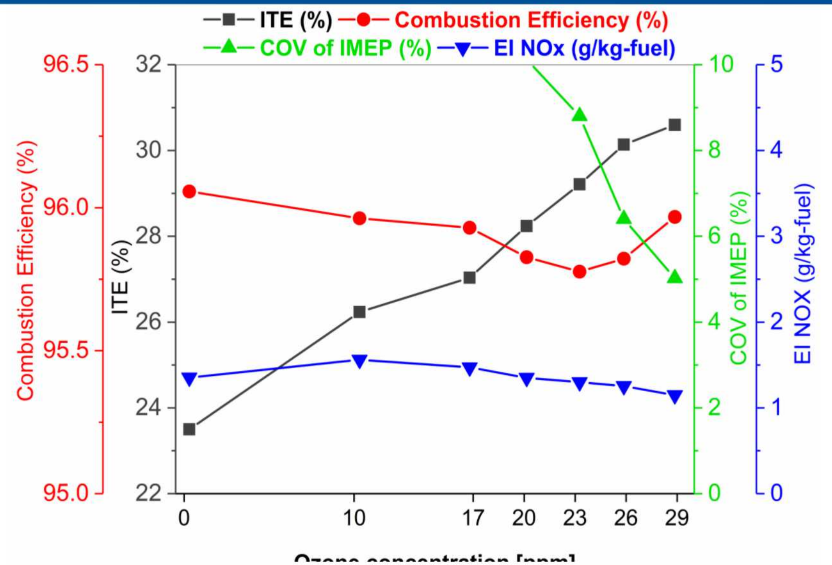
Sweep parameters

- O_3 concentration (0 – 34 ppm)
- Spark timing (70^0 – 28^0 bTDC)
- 2nd injection SOI (64^0 – 36^0 bTDC)
- Fuel split, 2nd injection fueling fraction 0 – 25%

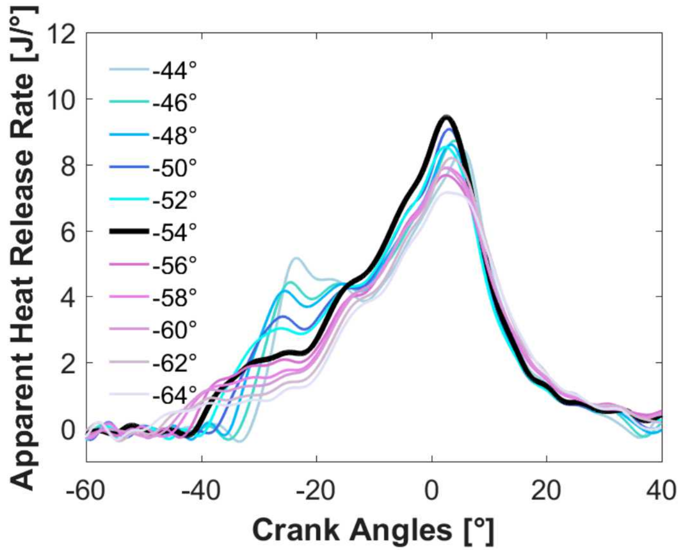
Baseline (1000 rpm, 2.8 bar IMEP) parametric sweep: O_3 and ST

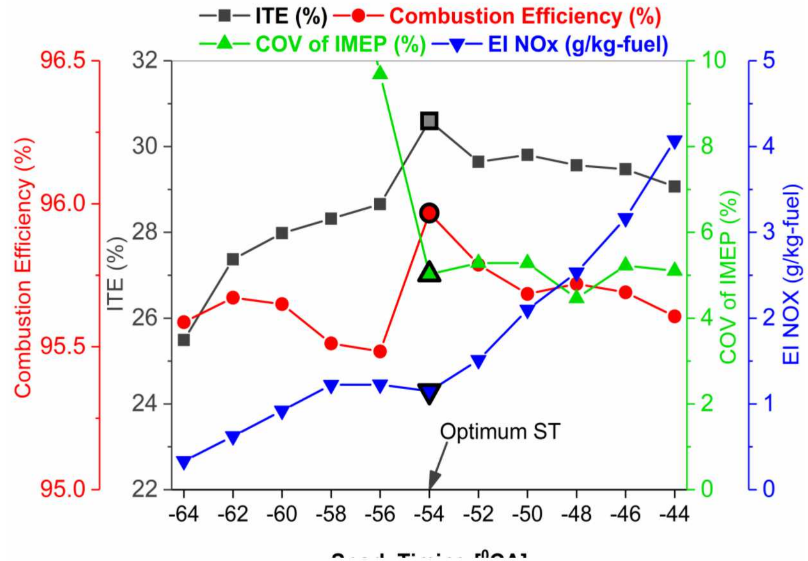
Ozone sweep





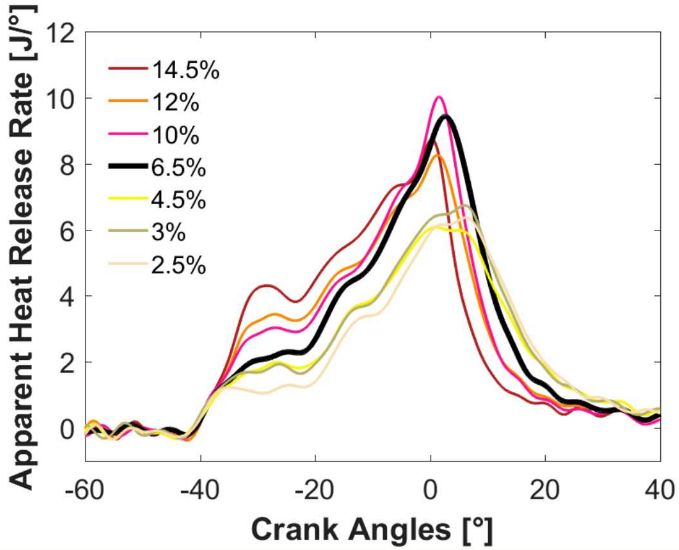
ST sweep

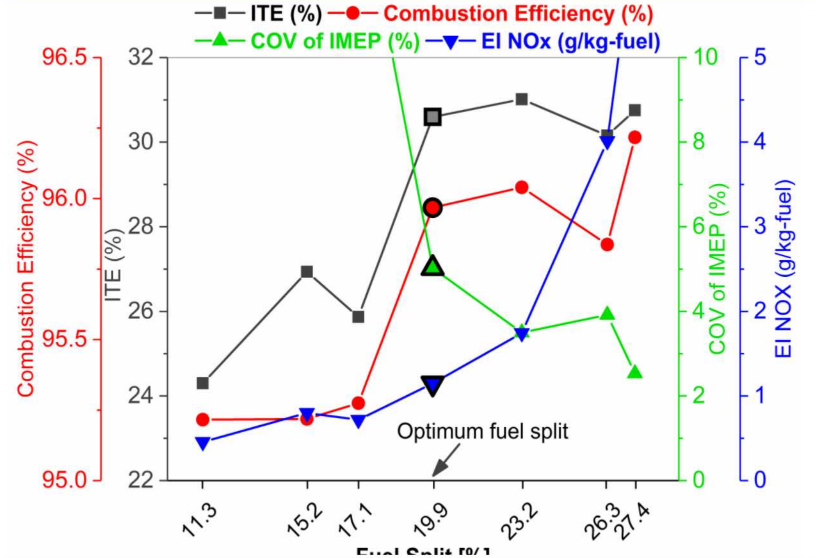




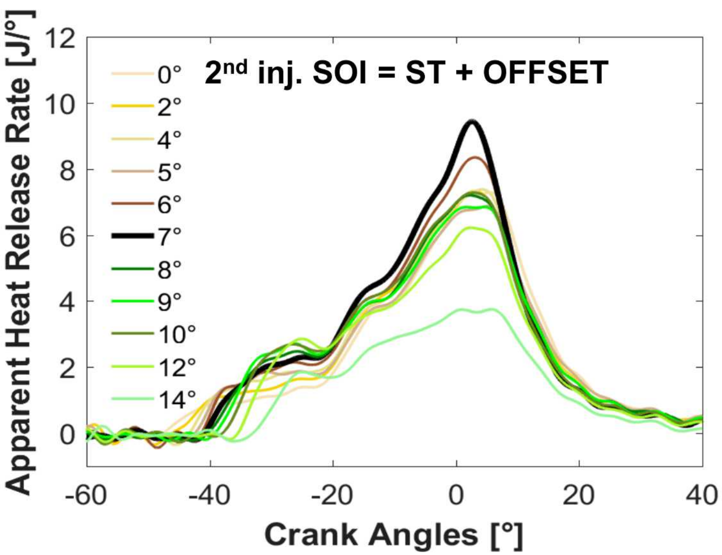
Baseline (1000 rpm, 2.8 bar IMEP) parametric sweep: Fuel split and 2nd inj. SOI

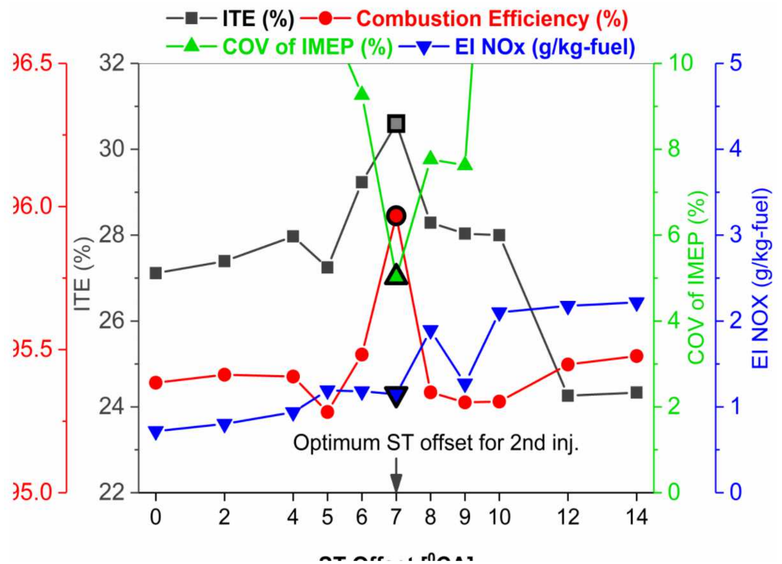
Fuel split sweep





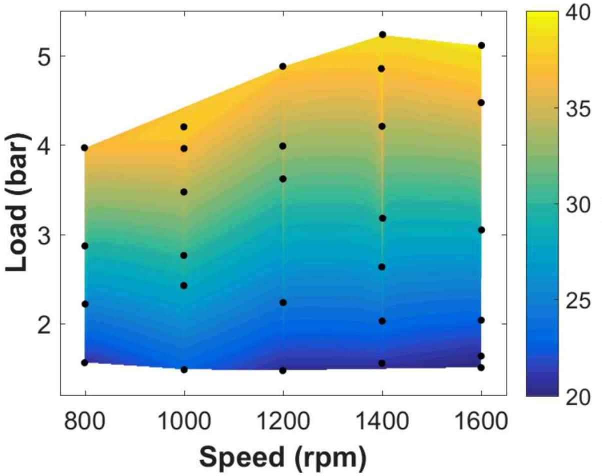
2nd inj. SOI



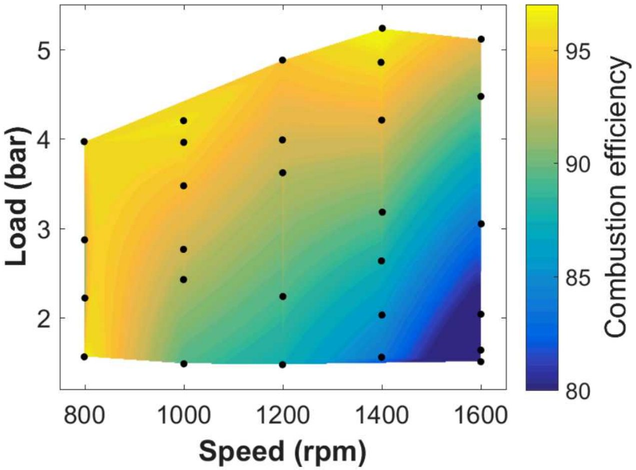


Effect of O_3: Engine performance

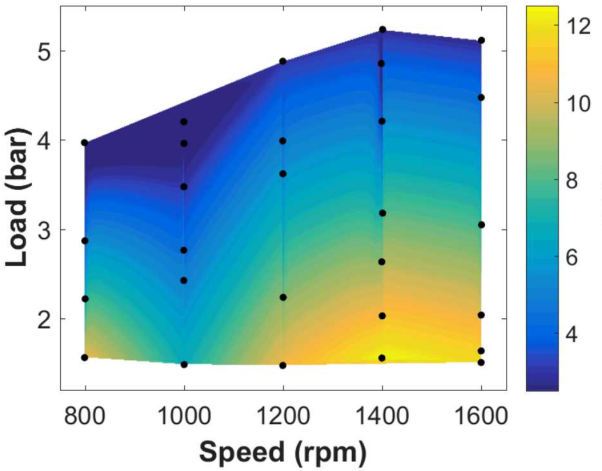
Indicated thermal efficiency



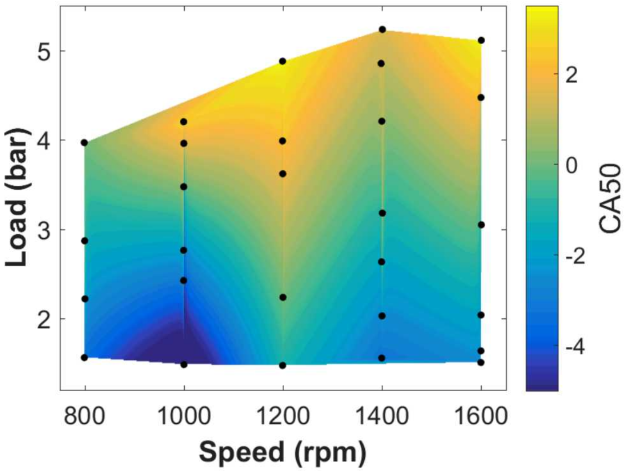
Combustion efficiency



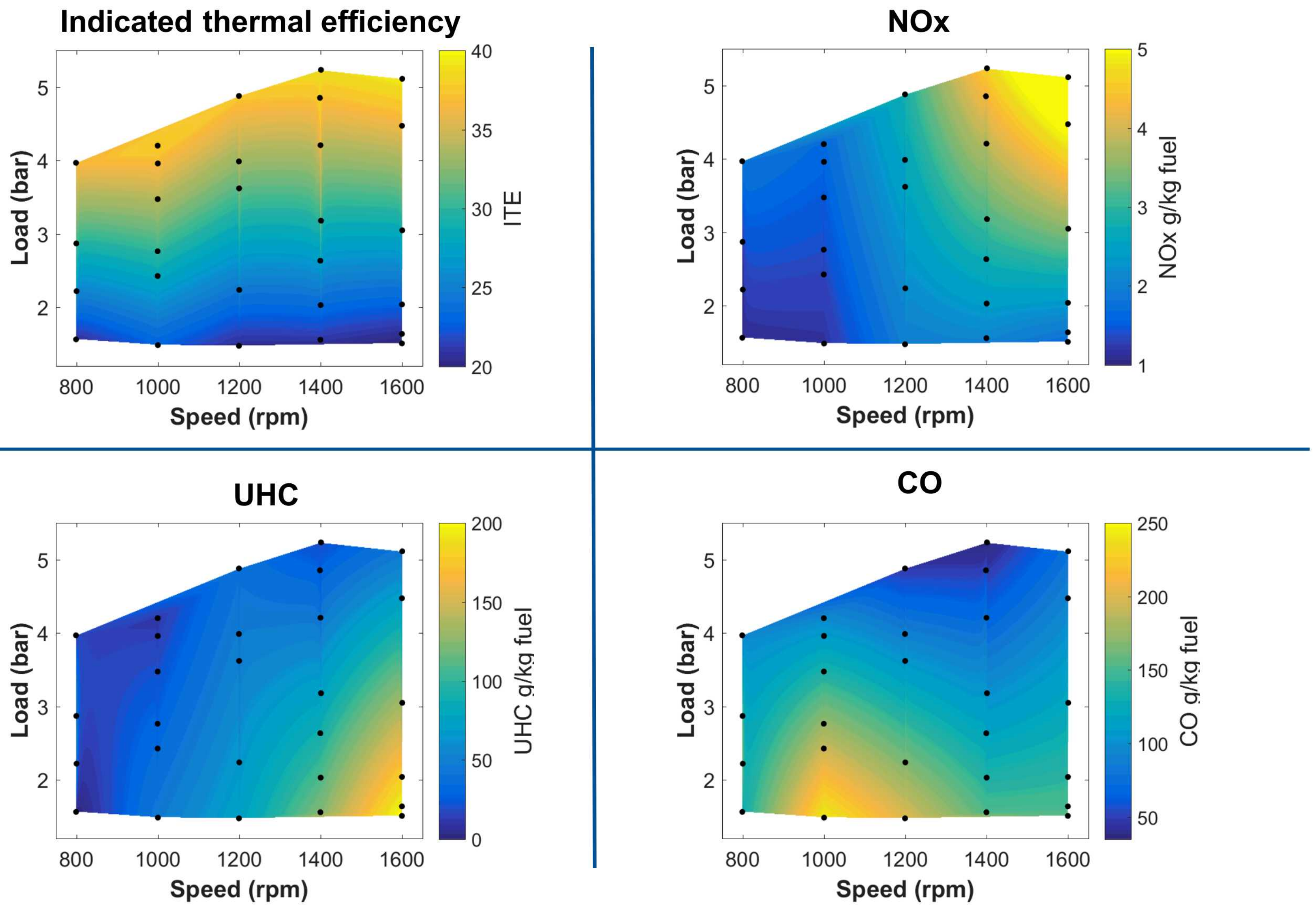
COV of IMEP (%)



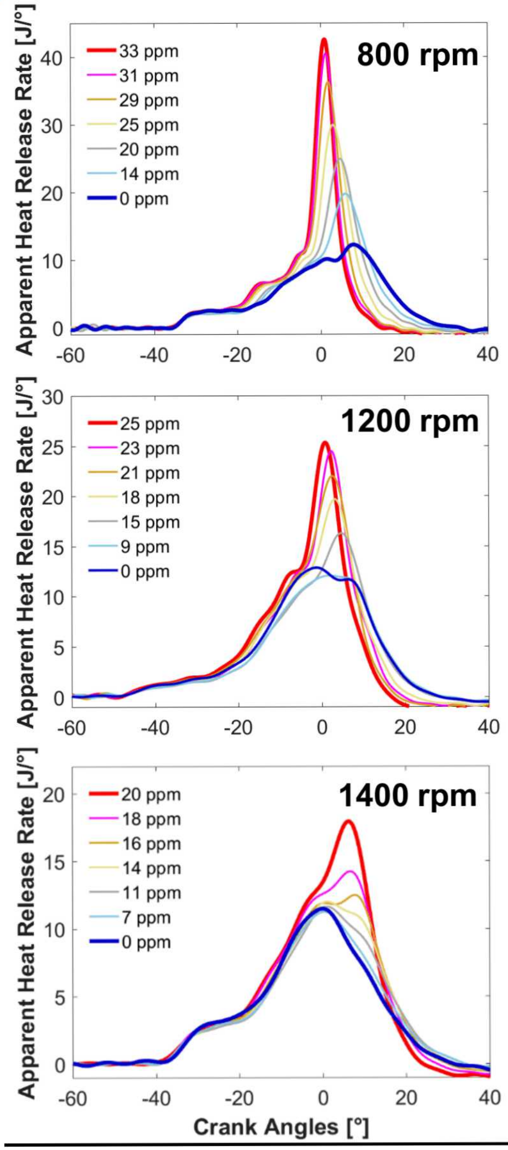
CA50



Effect of O_3: Emissions

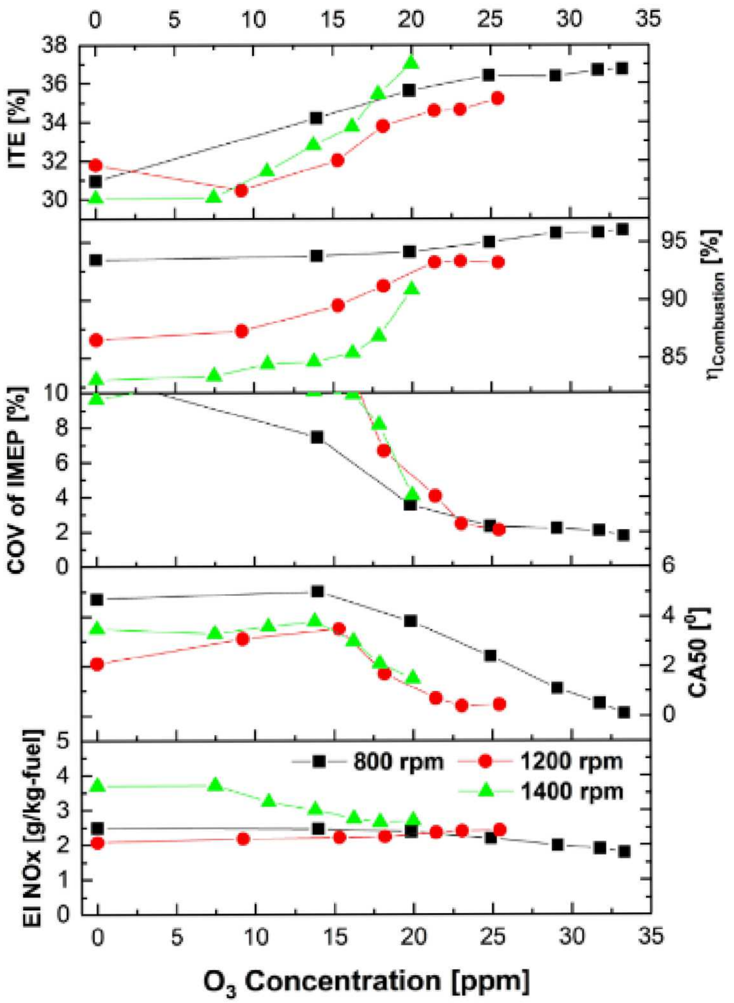


Effect of engine speed @Fixed load of 4 bar



- LTHR steadily weakened with increase in engine speed
- Higher O_3 increased end gas HTHR and advanced its phasing

- O_3 addition increases combustion efficiency, decreased cyclic variability, and produces optimal combustion phasing
- Peak ITE ~ 38%
- NOx emissions remained flat or declined with O_3 addition



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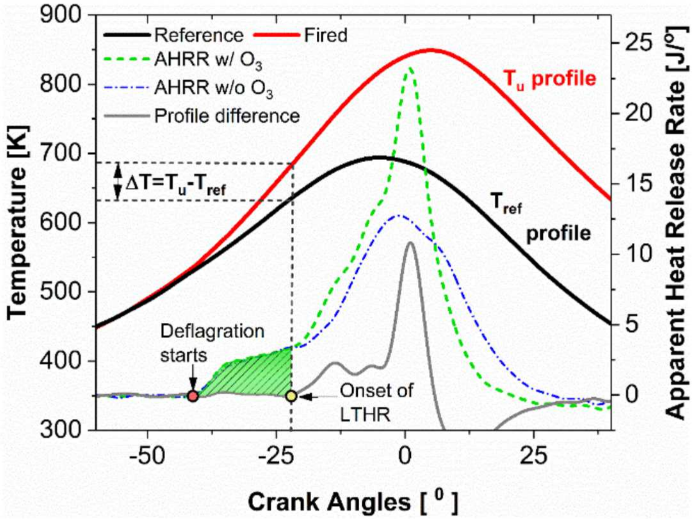
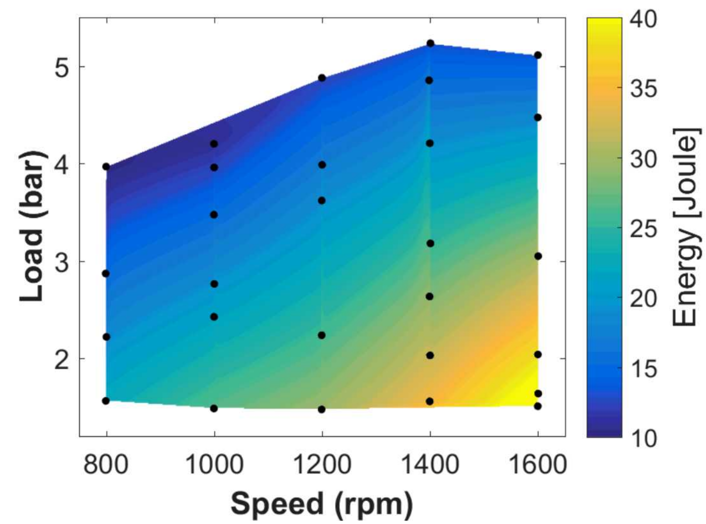
Energy requirements for end gas auto-ignition

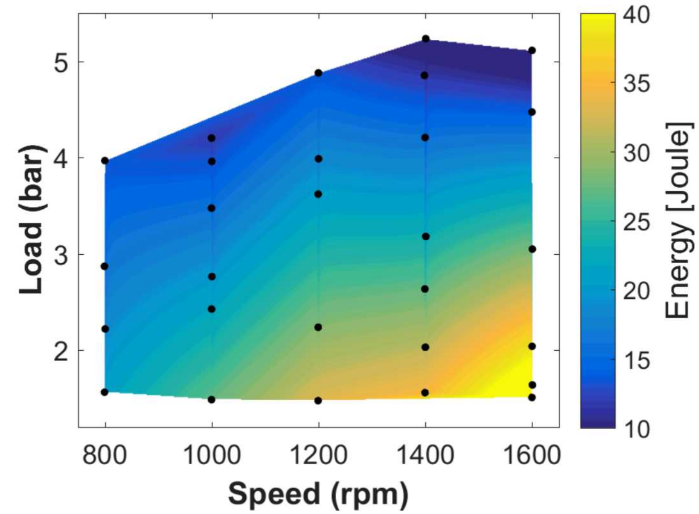
1200 rpm, 4.0 bar IMEP, 25 ppm O_3



Energy by integration



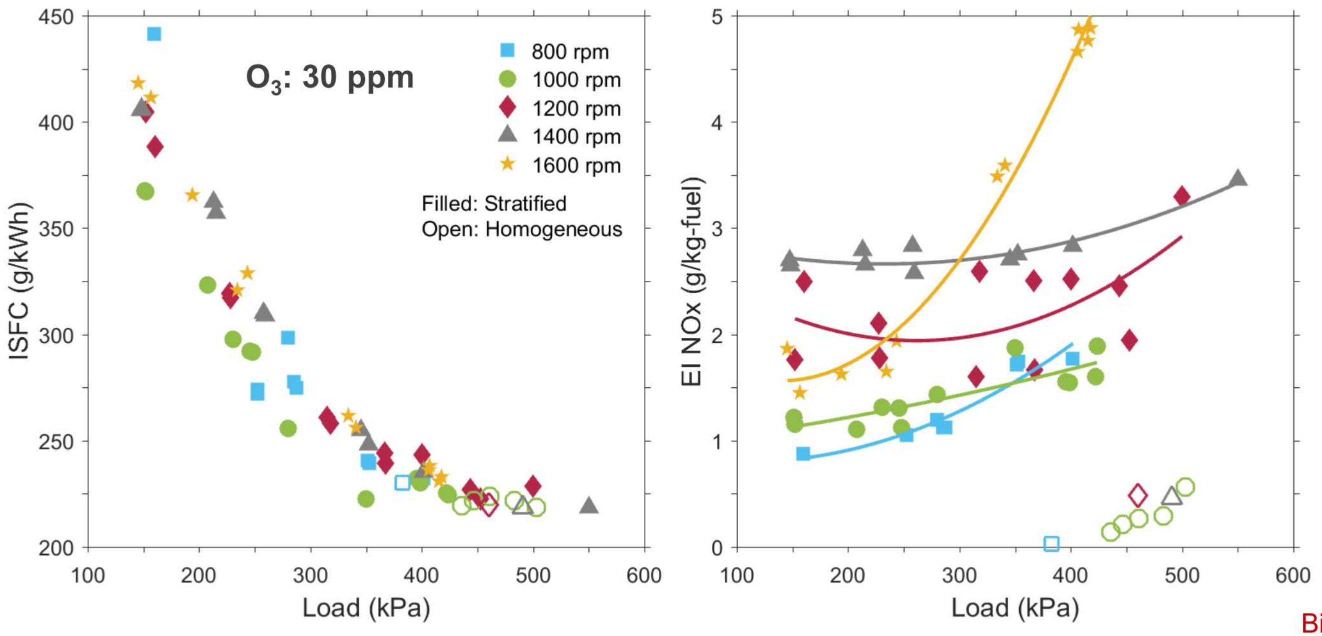
$$E = m_u C_{p,u}(T_{u,ref} - T_{u,SACI})$$



- End-gas auto-ignition ∝ added O_3
  - Effectiveness ↓ with engine speed ↑
- End-gas ΔT required for optimal auto-ignition increases with higher engine speeds & lower loads
- Good match between integrated heat release to LTHR onset and temperature difference methods

Conceptual model of end-gas energy requirements will enable development of a simplified modeling framework

O_3-addition greatly benefits SACI emissions & efficiency

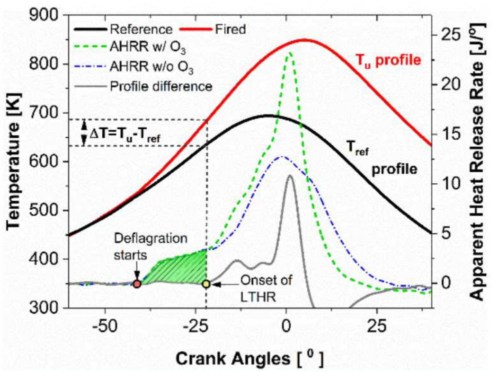


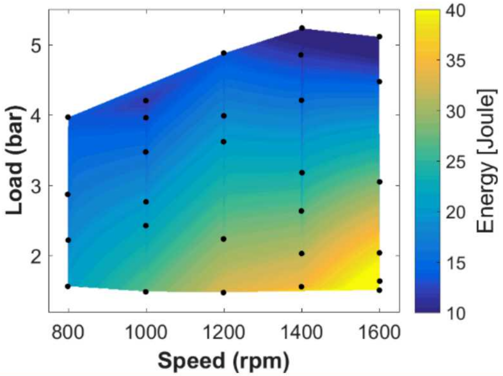
Biswas & Ekoto,
SAE WCX, Apr 2019

O_3-Enhanced SACI

- ***Partially Stratified Operation***
  - ↑ Robust speed/load range
  - ↑ 9% lower indicated specific fuel consumption (ISFC) w/ O_3 at lowest loads
  - ↓ Problematic nitrogen oxide (NOx) & particulate matter (PM) emissions
- ***Homogeneous Operation***
  - ↑ Similar efficiency to the partially stratified strategy
  - ↑ Ultra-low PM/NOx emissions
  - ↓ Does not work well at lower loads and higher speeds

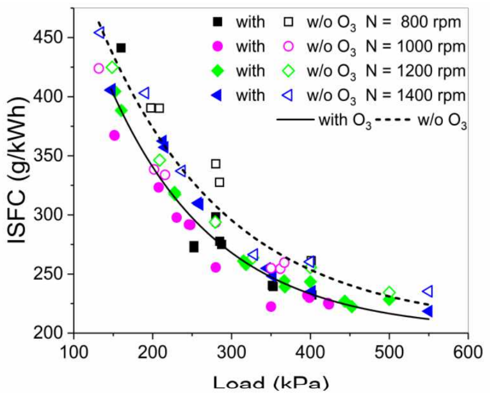
Summary



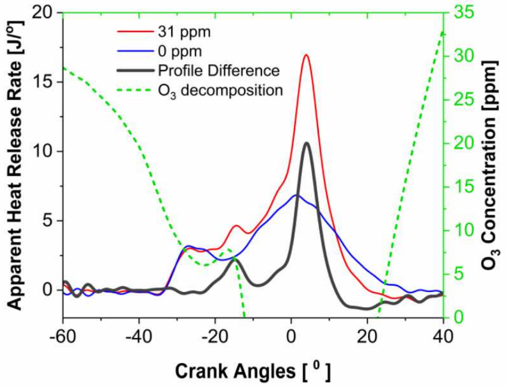


O_3 addition lowers the required thermal energy for auto-ignition

- Enables lower late-injection quantities, which helps to keep NOx/PM emissions under control



- Rapid decomposition of O_3 coincided with the onset of end-gas auto-ignition
- O_3 addition accelerates the onset of high-temperature heat release

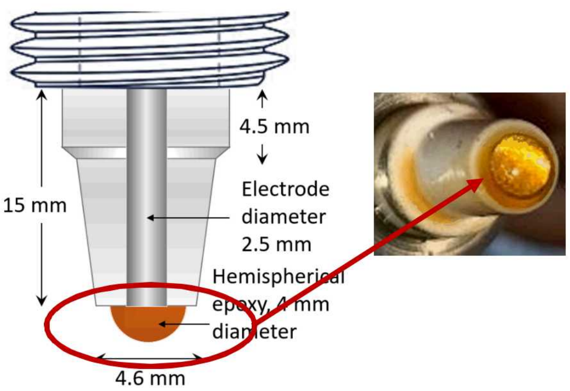


Up to 9% reduction in ISFC with O_3 addition enables controlled lean SACI operation for a range of low load/low speed conditions

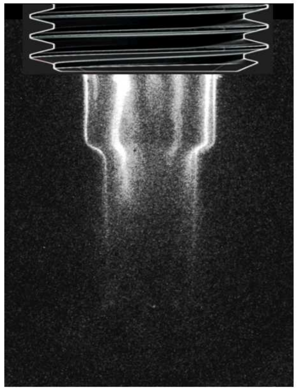
Advanced ignition has the potential to entirely eliminate 2nd injection

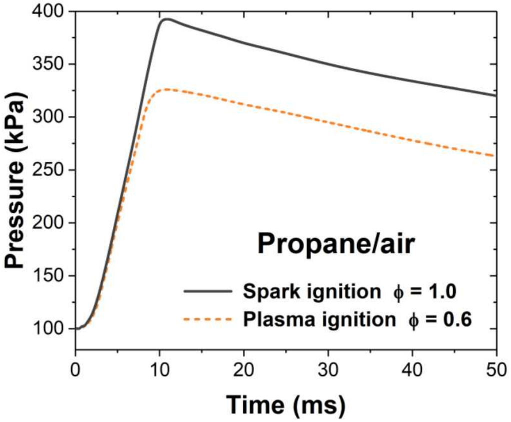
Low-temperature plasma igniters are advantageous for high-efficiency mixed-mode engine combustion

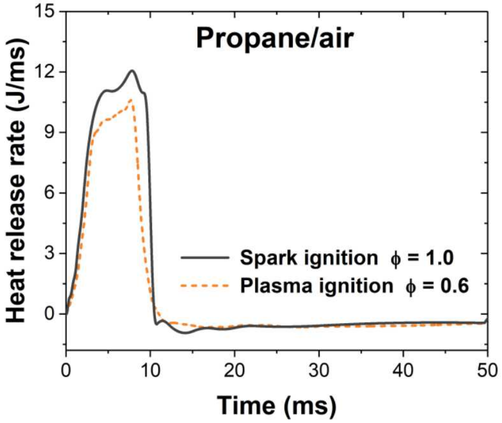
Plasma ignition produces stronger ignition kernels and faster flame propagation, expands dilute/lean ignition limits



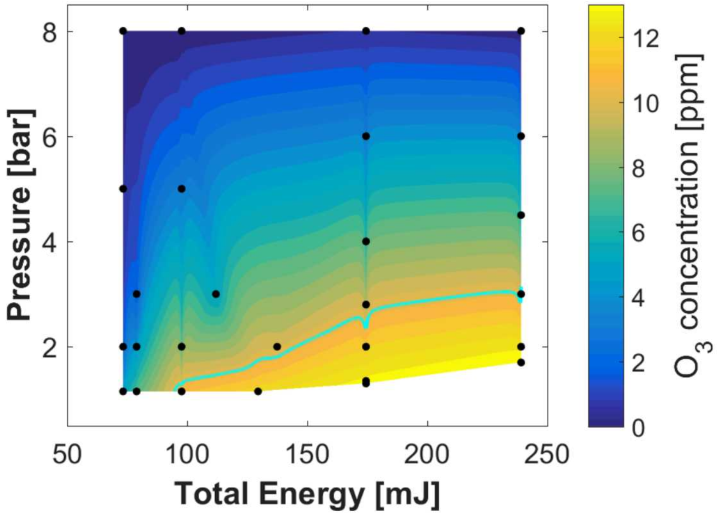
O* imaging







Plasma discharges in air produces enough O_3 to enable end gas auto-ignition



Cyan line represents 10 ppm of O_3

To generate 50 ppm of O_3, 50/10 = 5 bursts of 10 pulses are required (Total 50 pulses)

Thank you!