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Effects of Fuel Oxygenation and Ducted Fuel Injection on the Performance of a Mixing-Controlled Compression-Ignition Optical Engine Equipped with a Two-Orifice Fuel Injector

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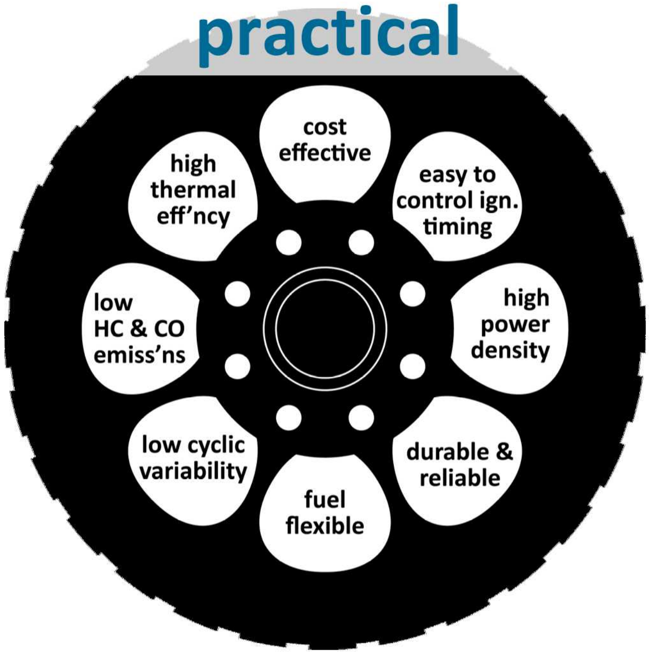
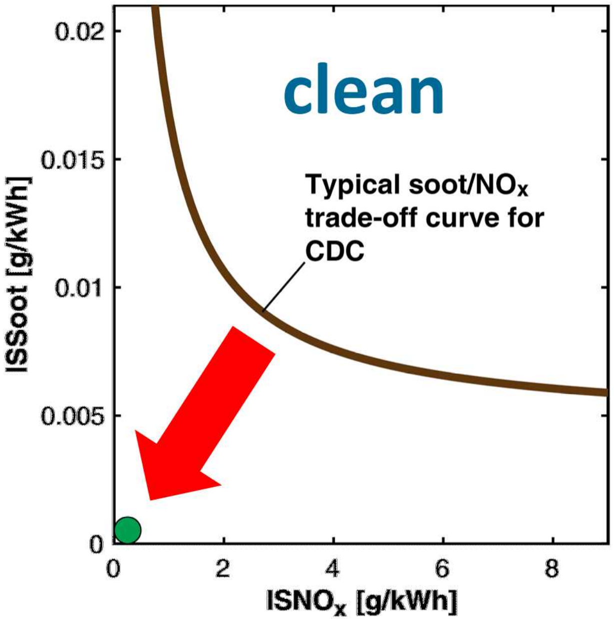
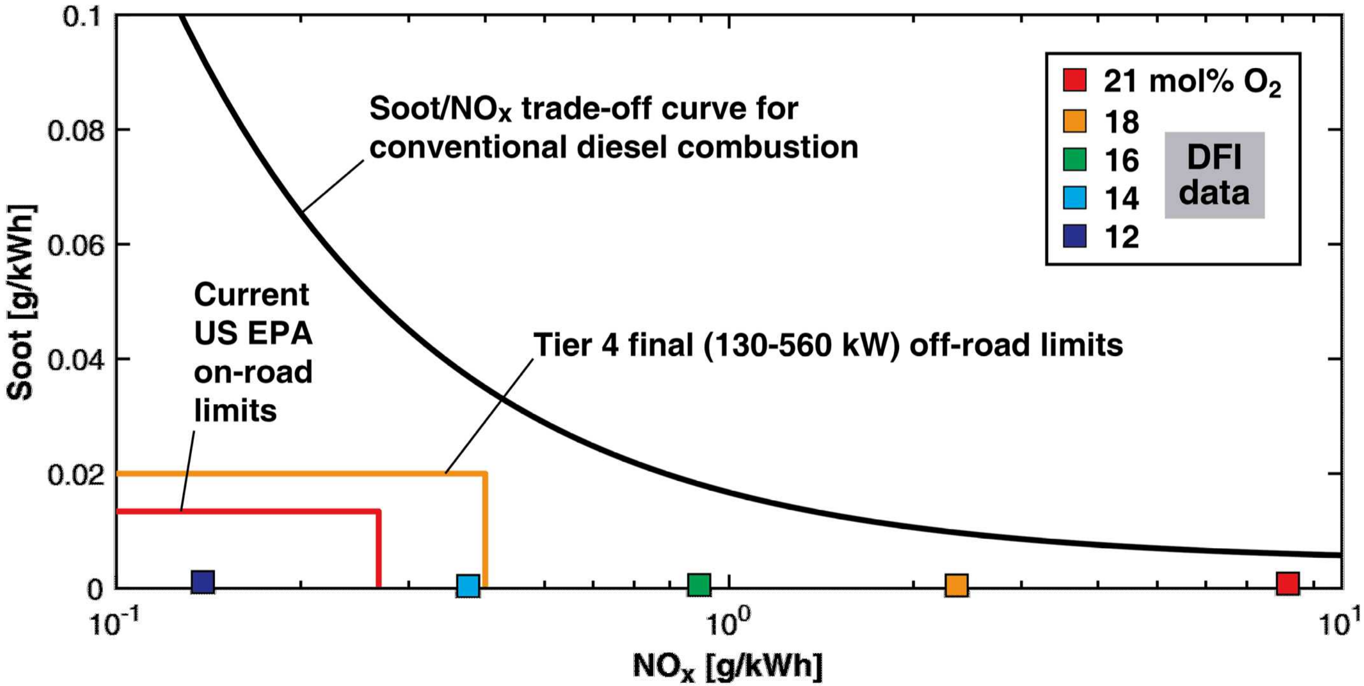
Objective: Maintain all the desirable attributes of conventional diesel combustion (CDC)…





…with 10X – 100X lower soot & nitrogen oxides (NO_x) emissions
…while harnessing synergies with sustainable, home-grown fuels.

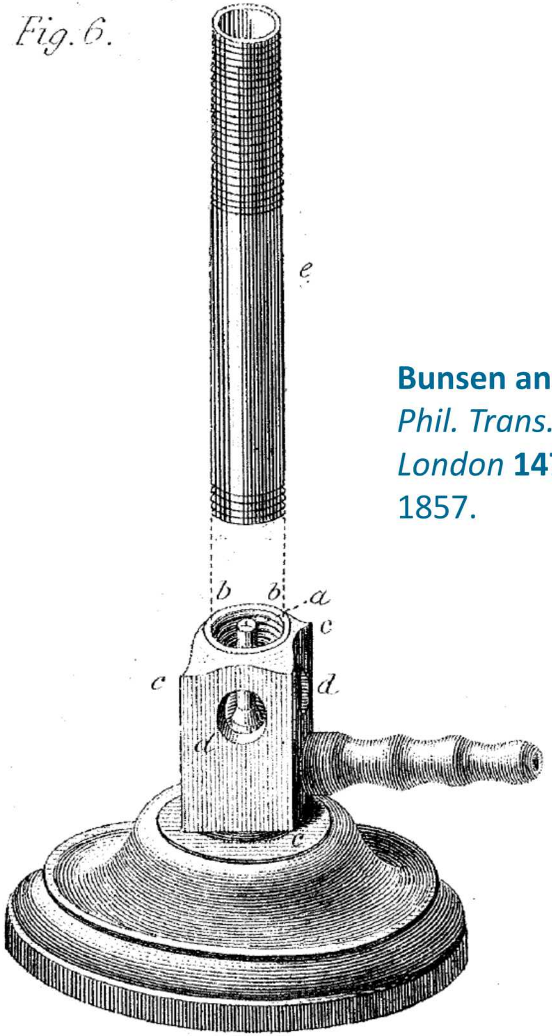
Ducted fuel injection (DFI) shows promise for achieving large, simultaneous reductions in engine-out soot & NO_x:



- With dilution, DFI can break the long-standing diesel soot/NO_x trade-off, even with current diesel fuel.

What is DFI?

- **A simple, mechanical approach to improve diesel combustion**
  – Motivated by Bunsen burner concept



Bunsen and Roscoe, *Phil. Trans. Royal Soc. London* **147**:355-380, 1857.

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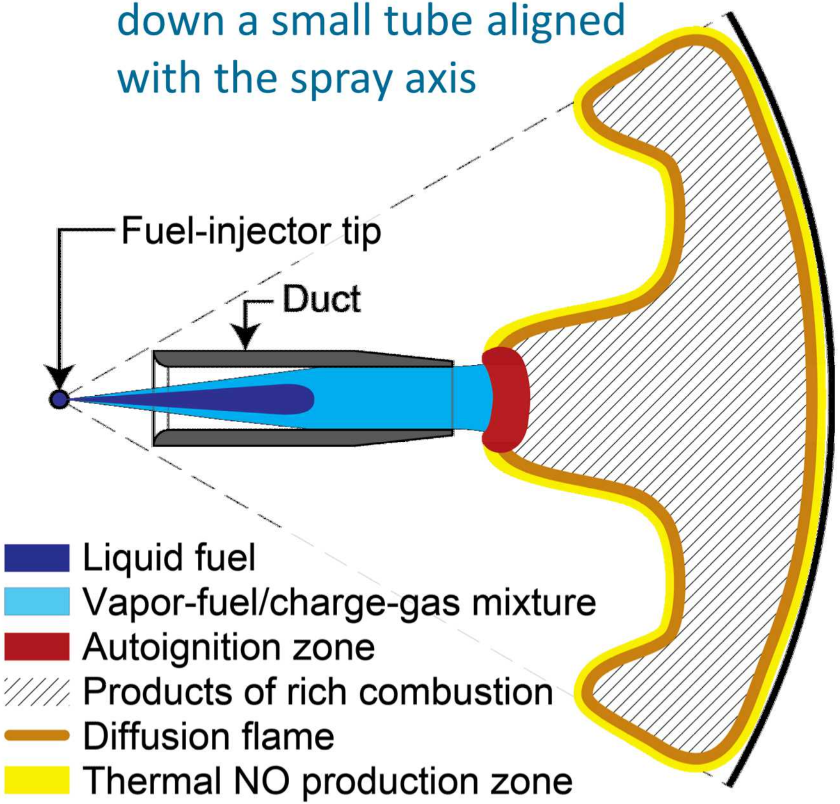
  - A refinement of CDC → behaves similarly

Basic idea: inject the fuel spray down a small tube aligned with the spray axis



C.J. Mueller et al., doi:10.1016/j.apenergy.2017.07.001

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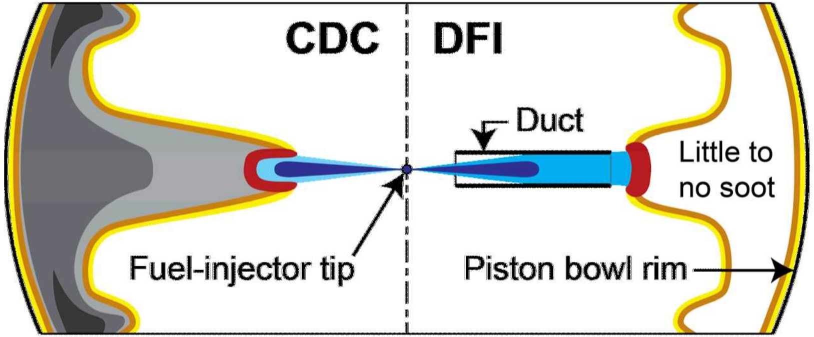
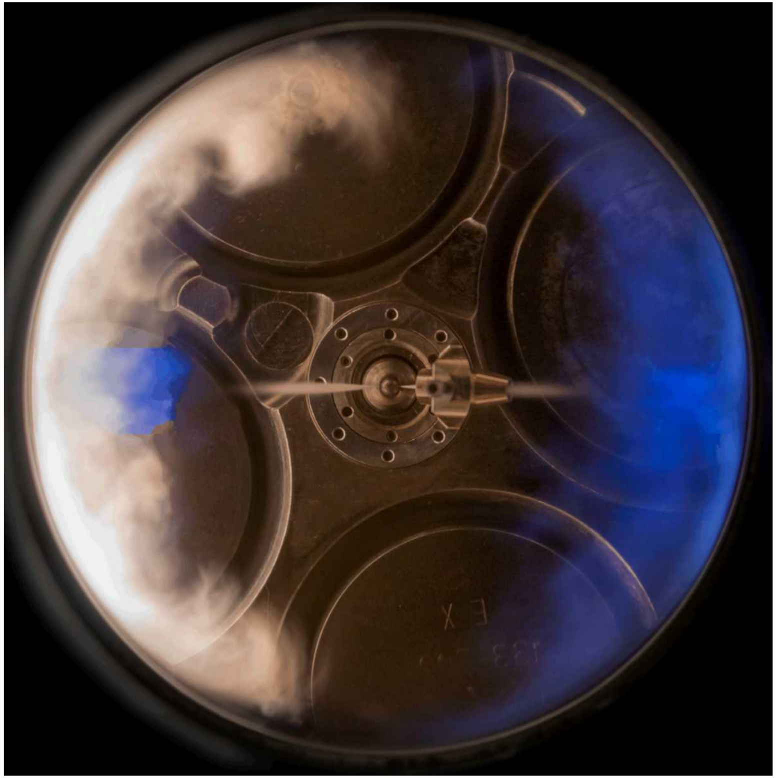
- **Effective at curtailing/eliminating soot**





S. Ashley, https://www.scientificamerican.com/article/can-diesel-finally-come-clean/

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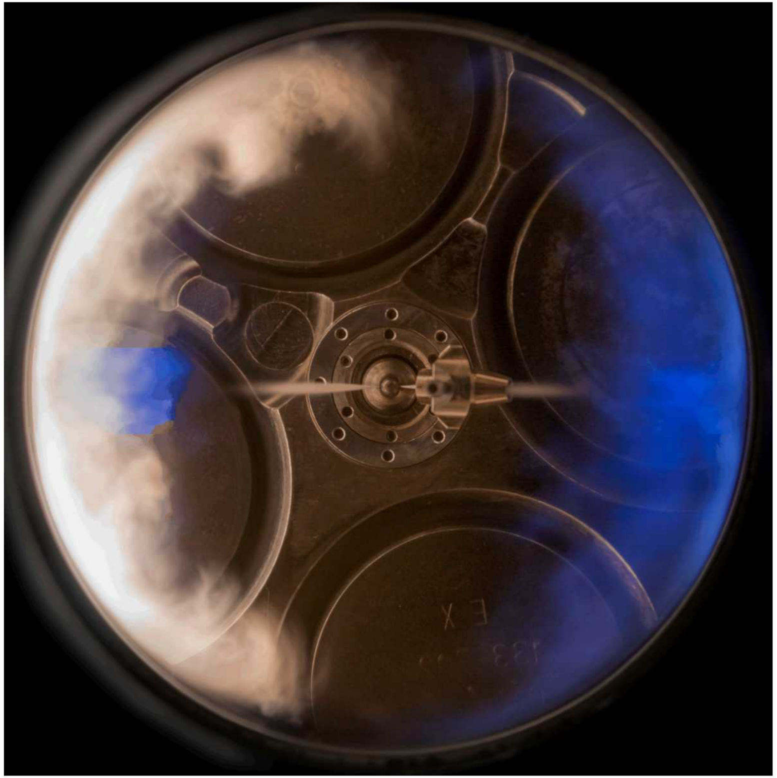
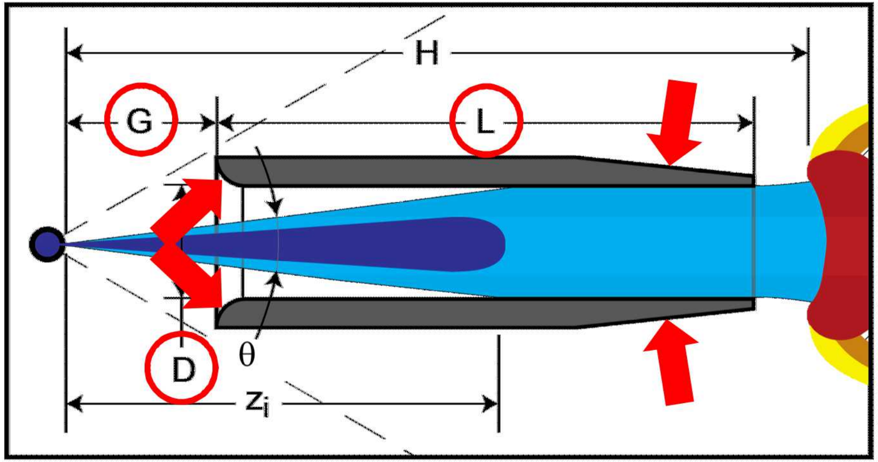
- **Tolerant to dilution for cost-effective NO_x control**

Can renewable, oxygenated fuels provide additional benefits?

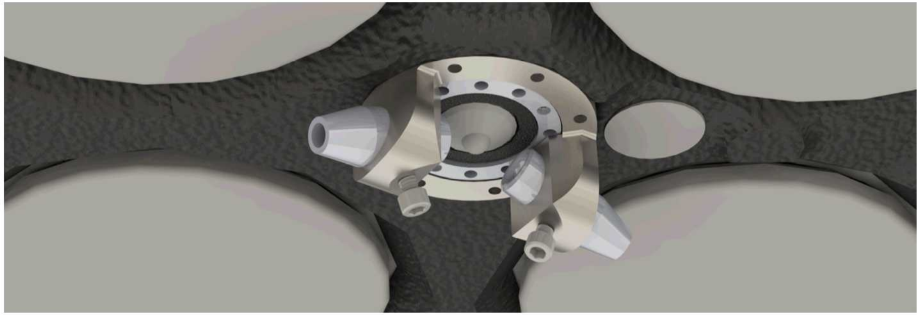


S. Ashley, https://www.scientificamerican.com/article/can-diesel-finally-come-clean/

Experimental setup: Two (2) duct assembly

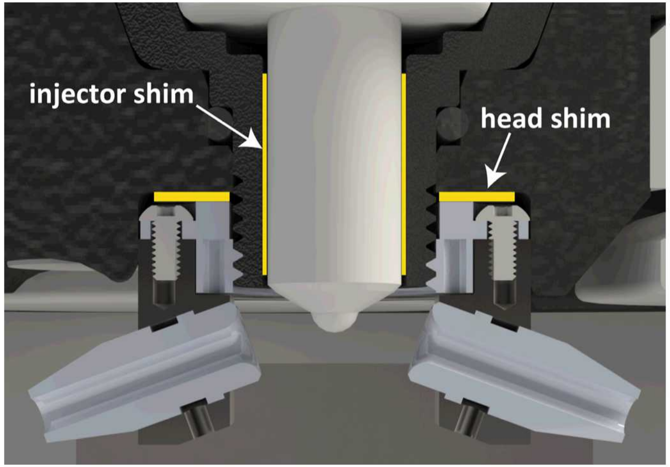


- **Key duct parameters** D2L12G3δ
  - Inner diameter (D [mm])
  - Length (L [mm])
  - Standoff distance (G [mm])
  - Inlet/outlet shape (Greek letter)

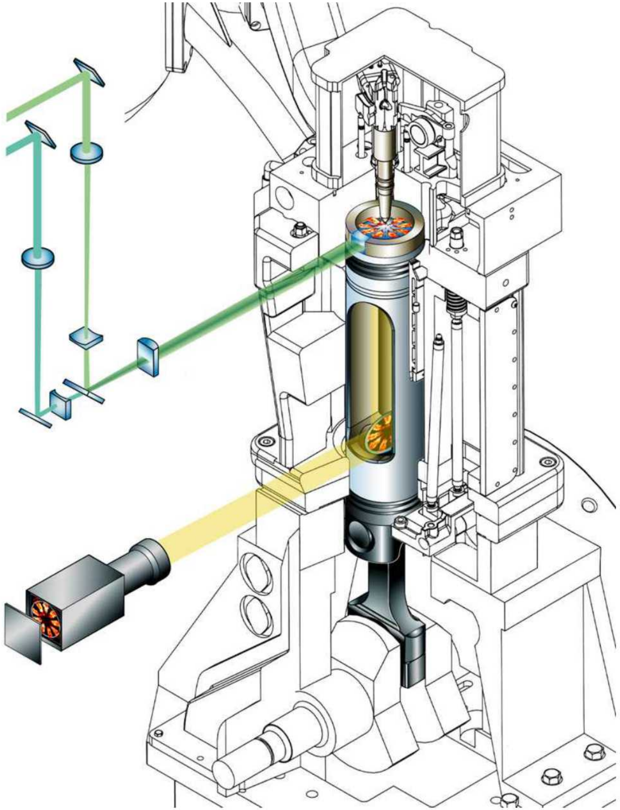


D2L12G3δ configuration was used for all exp'ts reported herein.

Duct/holder fabricated from 304 SS.



Experimental setup: Optical engine



Research engine	Single-cylinder
Cycle	4-stroke CIDI
Valves per cylinder	4
Bore	125 mm
Stroke	140 mm
Displacement per cyl.	1.72 liters
Conn. rod length	225 mm
Conn. rod offset	None
Piston bowl diameter	90 mm
Piston bowl depth	16.4 mm
Squish height	1.5 mm
Swirl ratio	0.59
Compression ratio	12.5:1
Simulated compr. ratio	16.0:1

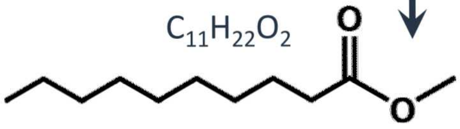
- Cylindrical piston bowl with flat bottom

- Solenoid common-rail fuel injector

Experimental matrix

- **Three (3) fuels:**
  - **CFB** = No. 2 S15 emissions certification diesel fuel
  - **MD25** = 25 vol% methyl decanoate (ester) in CFB

$C_{11}H_{22}O_2$

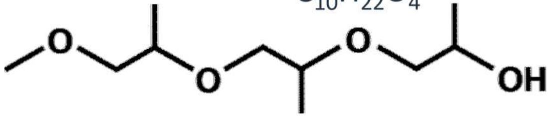


$$\phi_{\Omega,MD25} = \frac{2n_C + \frac{1}{2}n_H}{n_O} = 73.4$$

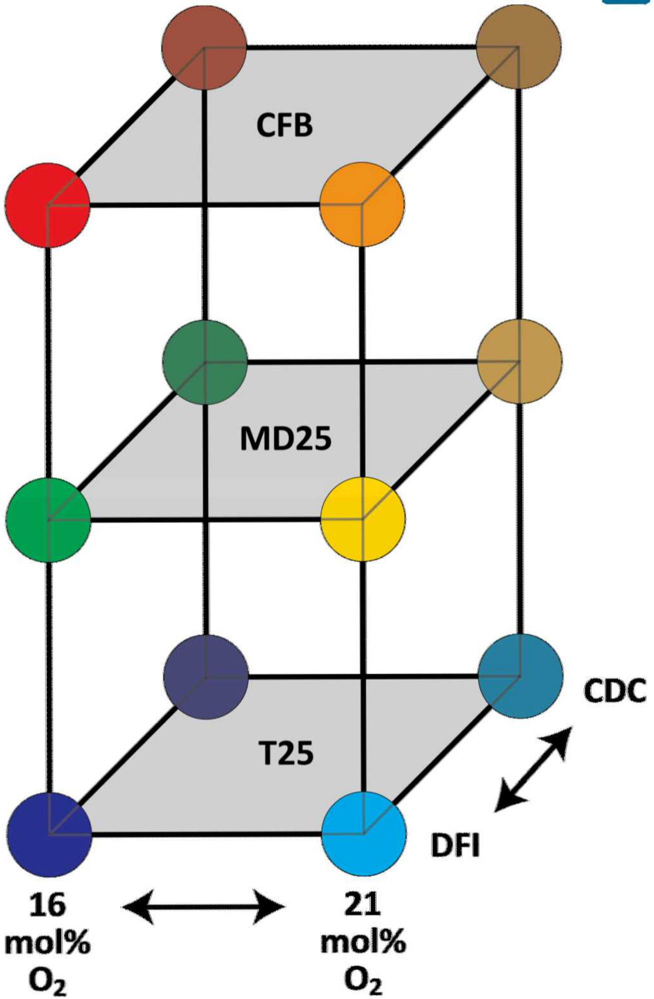
(see SAE 2005-01-3705 for details)

  - **T25** = 25 vol% tri-propylene glycol mono-methyl ether in CFB

$C_{10}H_{22}O_4$



$$\phi_{\Omega,T25} = 36.3$$



- **Two (2) dilution levels: 16 & 21 mol% O_2**
- **Two (2) combustion strategies: DFI vs. CDC**

Operating conditions & diagnostics

Engine speed	1200 rpm
Load (gross IMEP)	~2.6 bar
Injector tip	2 × 0.108 mm × 140°
Injection pressure	180 MPa
Injected energy	1.22 kJ
Injection schedule, duration	Single inj., 3.4-3.7 ms
Start of combustion timing	TDC
Intake manifold abs. press.	2.00 bar ≈ 1.3 bar ME*
Intake manifold temperature	90 °C ≈ 21 °C ME*
Coolant temperature	90 °C
Fired cycles per run	180
Runs per condition	≥ 3

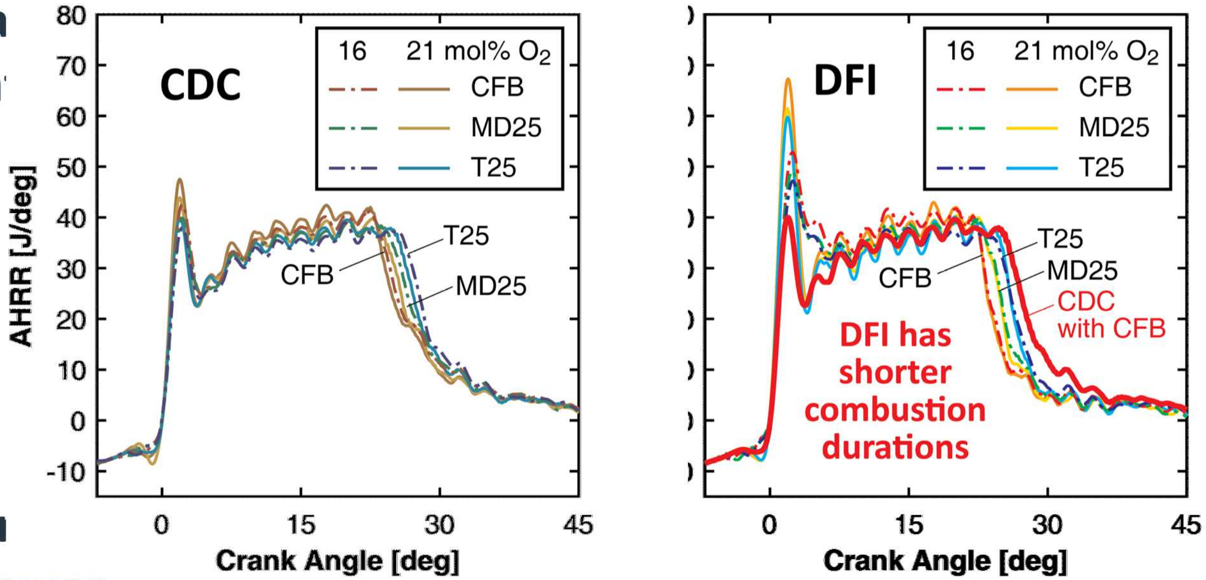
**ME = corresponding intake conditions for a metal engine with a 16.0:1 compression ratio*

- **Cylinder pressure**
  - Apparent heat-release rate, temperature
- **Engine-out emissions**
  - Smoke, NO_x, HC, CO, O_2, & CO_2
- **Fuel injection**
  - Mass & rate
- **Natural luminosity**
  - Spatially integrated natural luminosity (SINL)
    - A sensitive but qualitative measure of hot in-cyl. soot

Results

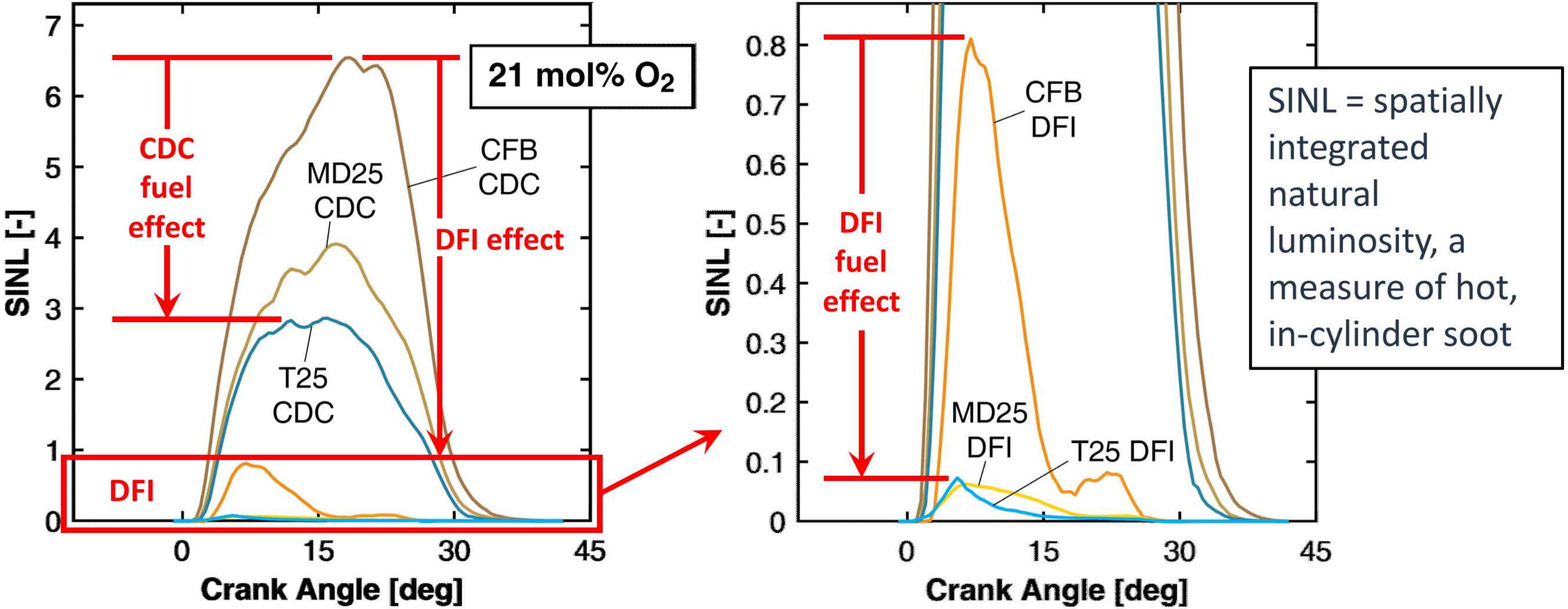
DFI with two ducts has been tested successfully in the optical engine with diesel fuel & two oxygenates.

- **DFI exhibits apparent hea release rates (AHRRs) tha are similar in shape & features to CDC**
  - DFI has larger pre-mixed burns & slightly shorter combustion durations than CDC



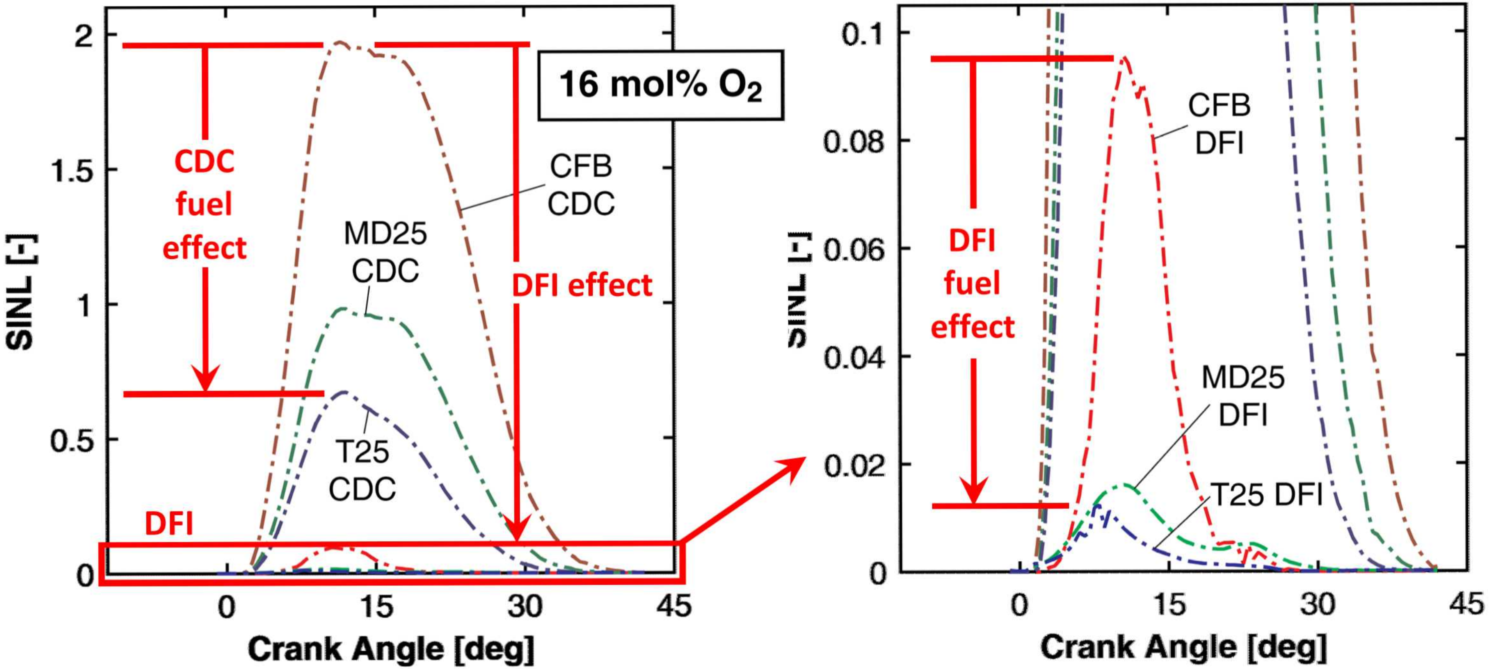
- **AHRR is slightly longer fo oxygenates due to their lower energy densities & correpondingly longer injection durations**
  - T25 has approximately twice the oxygen content of MD25

Both fuel oxygenation & DFI are effective at curtailing incandescence from in-cylinder soot (no dilution).



- Changing from CDC to DFI lowers SINL more than adding 25 vol% of either oxy.
- Fuel effect is larger for DFI than for CDC (on a percentage basis)

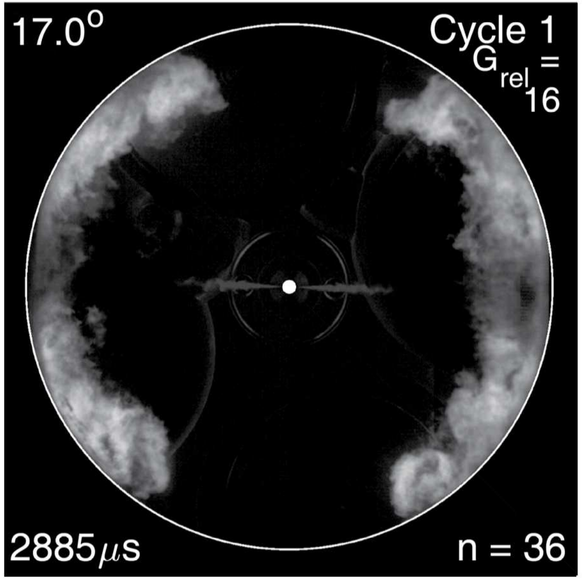
Similar trends are observed under dilute conditions.



- Changing from CDC to DFI lowers SINL more than adding 25 vol% of either oxy.
- Fuel effect is larger for DFI than for CDC (on a percentage basis)

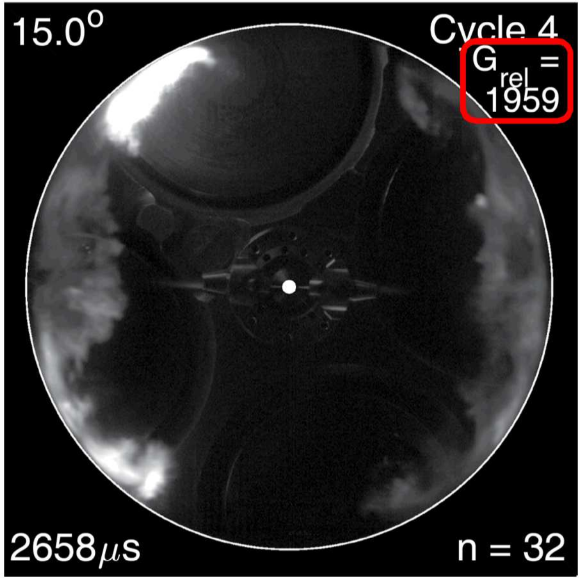
Fuel oxygenation & DFI together can curtail SINL by ~100X on average, often preventing soot formation.

CFB CDC @ 16 mol% O_2



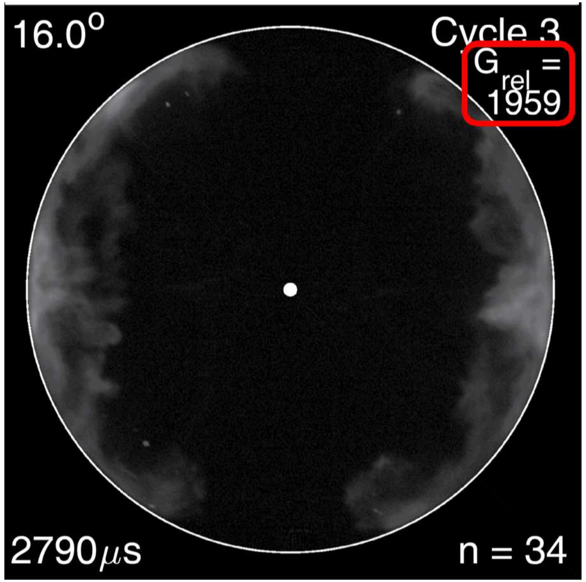
Status quo:
Significant engine-out soot

MD25 DFI @ 16 mol% O_2



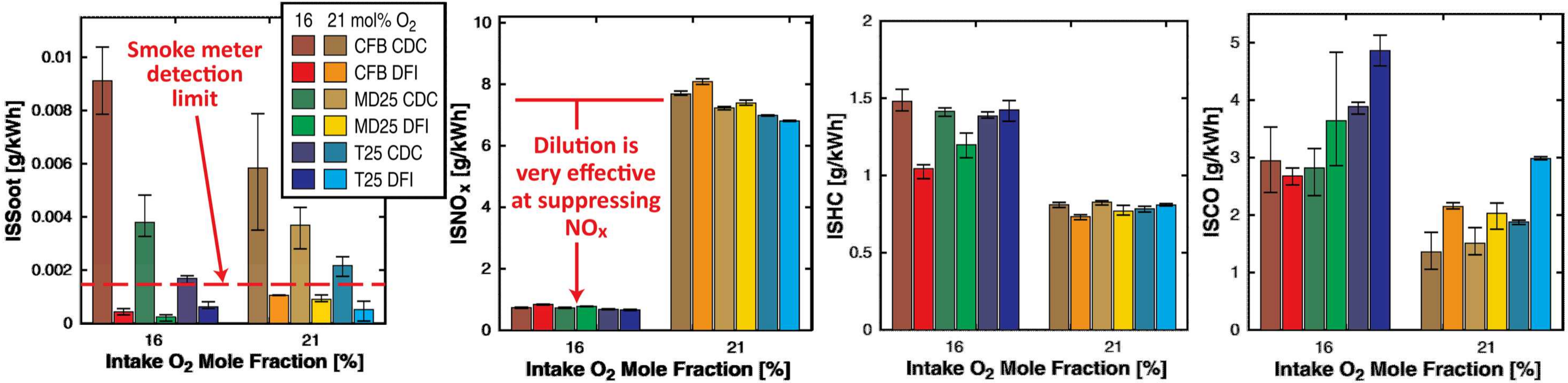
Transition:
“Zero” engine-out soot

T25 DFI @ 16 mol% O_2



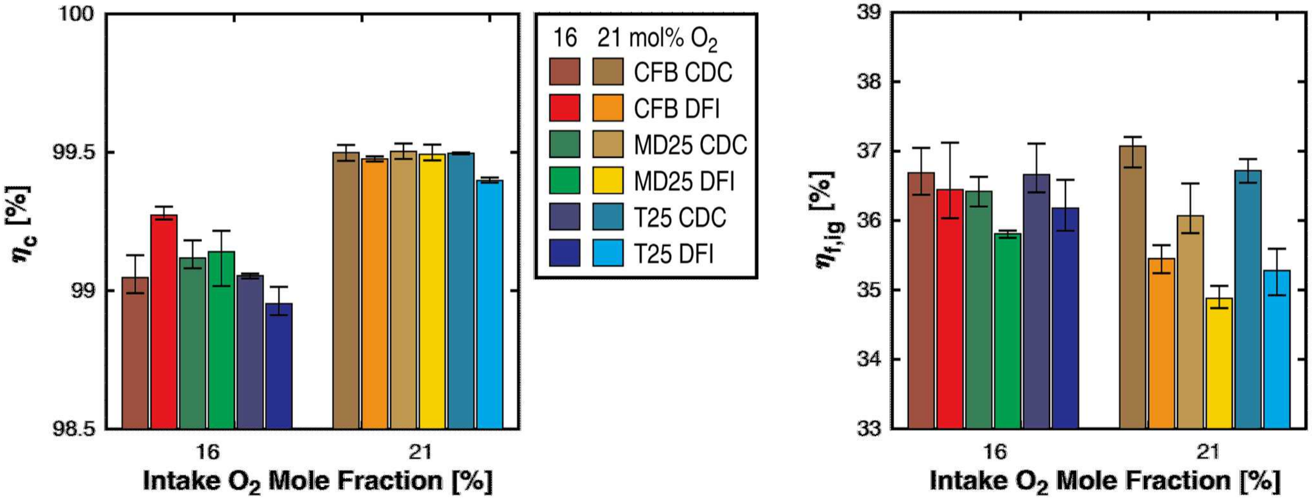
Leaner lifted-flame combust. (LLFC): “Zero” in-cyl. soot

Aside from much lower soot, DFI with oxygenated fuels produces emissions levels similar to those for CDC.



- Indicated specific (IS) soot emissions track with SINL trends from movies
- $ISNO_x$ typically ↓ with fuel oxygenation
- ISHC is typically maintained or improved via oxygenation & DFI
- ISCO typically ↑ with oxygenation & DFI; levels controllable with oxi-cat

Combustion & fuel-conversion efficiencies are similar between DFI & CDC.



- Combustion efficiencies (η_c) are typically $\geq$ 99%, may ↑ or ↓ with fuel & DFI
- Fuel-conversion efficiencies ($\eta_{f,ig}$) typically ↓ with oxygenation (< 1.0% abs.) & with DFI (< 1.6% abs.)
  - Likely due to ↑ inj. duration & ↑ heat transfer to piston bowl wall, respectively

Conclusions

- **DFI with only 25 vol% of an oxygenated fuel can:**
  - Attenuate soot incandescence by ~100X
    - ~10X from DFI, ~10X from fuel oxygenation
    - Without large impacts on other emissions, efficiency, or controllability
  - Facilitate operation at low-NO_x conditions (via dilution) that aren't otherwise feasible due to excessive soot
  - Thereby enable simultaneous reductions in MCCI engine-out soot & NO_x
- **Even with current diesel fuel, DFI can enable simultaneous, orders-of-magnitude reductions in engine-out soot & NO_x emissions**
  - Importance of fuel oxygenation is likely to increase with engine load

DFI with oxygenated, renewable fuels provides a promising potential path to practical, clean, and sustainable transportation for the future.