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An Introduction to Ducted Fuel Injection

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Emerging Heavy-Duty Technologies Session
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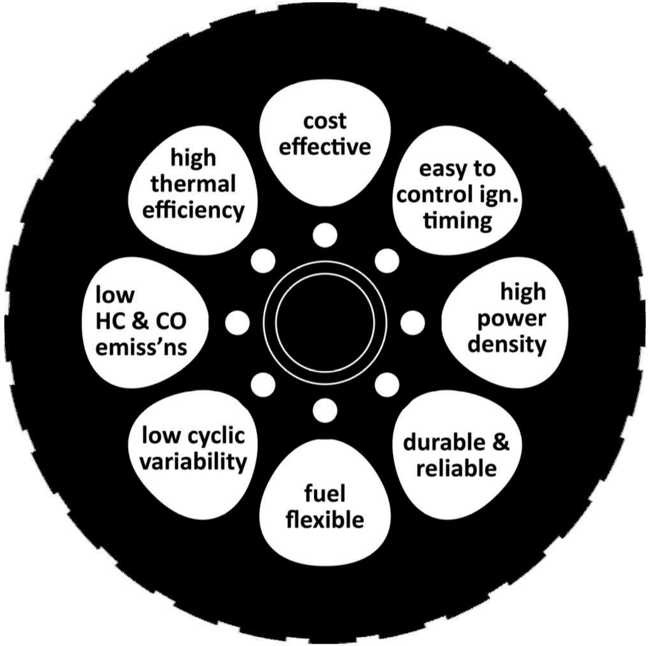
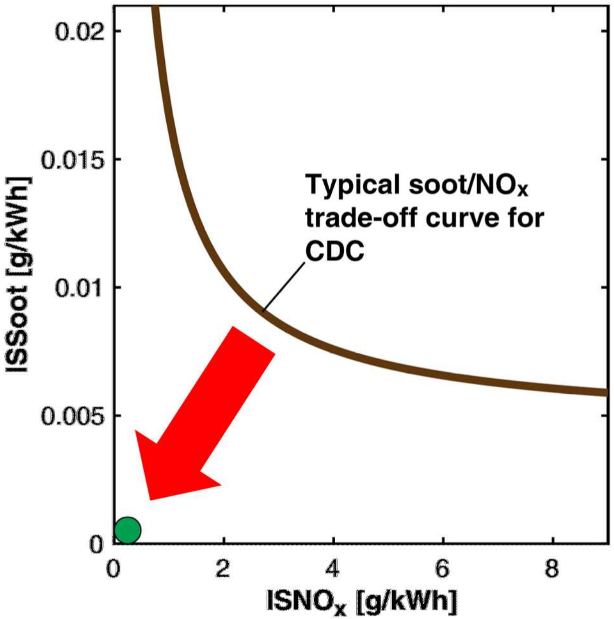
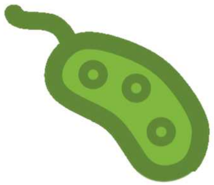
Objective: Maintain all the desirable attributes of conventional diesel combustion (CDC)…



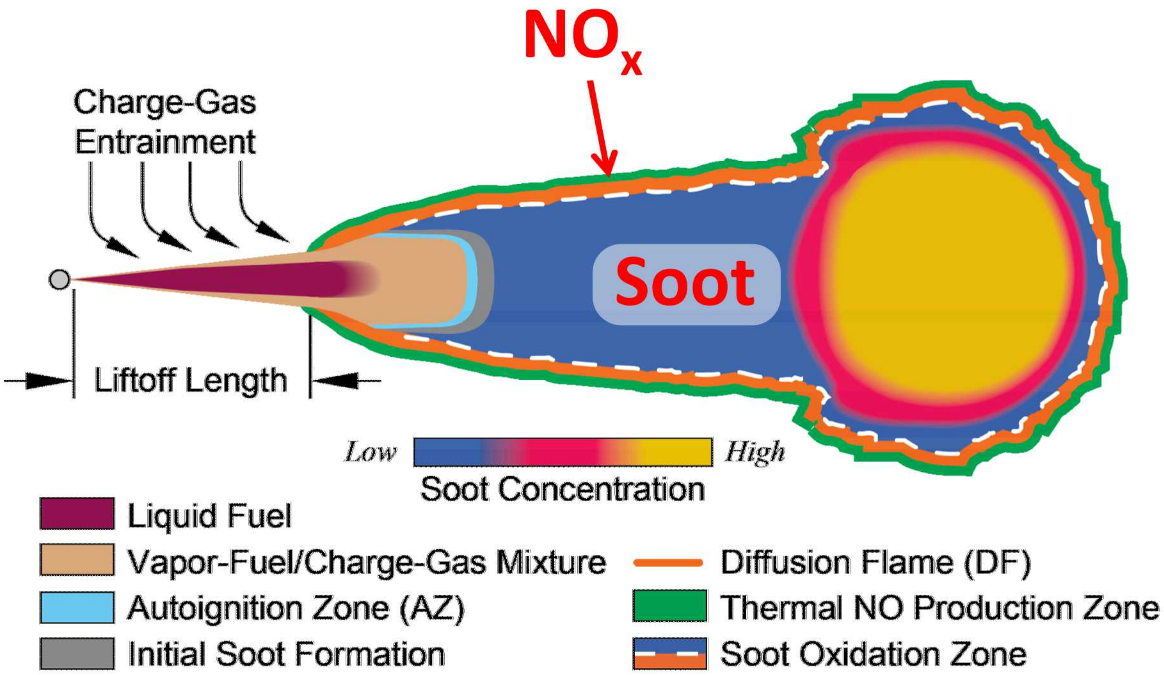




…with 10X – 100X lower soot & nitrogen oxides (NO_x) emissions
…while harnessing synergies with sustainable, home-grown fuels.

What is mixing-controlled compression-ignition (MCCI) combustion?

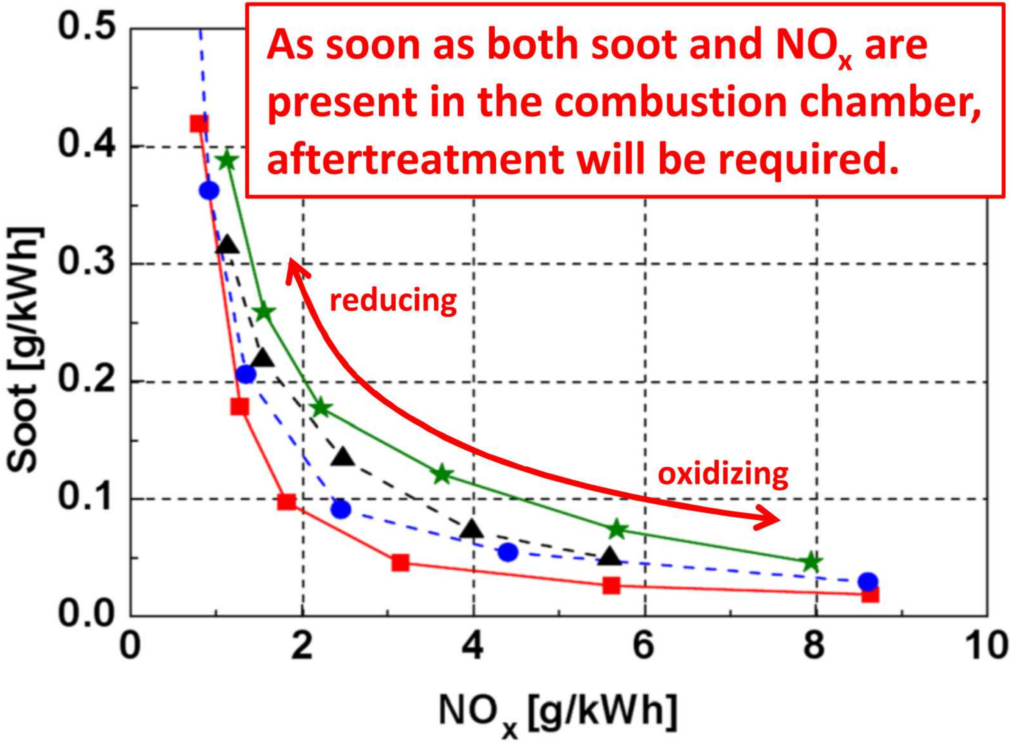
- **CI combustion where ignition & the majority of the heat release occur during the fuel-injection event**
  - This distinguishes it from globally premixed approaches
    - E.g., SI, ACI, LTC, PPCI,…
- **Conventional diesel combustion (CDC) is the classic example of MCCI**



Dec, doi:10.4271/970873

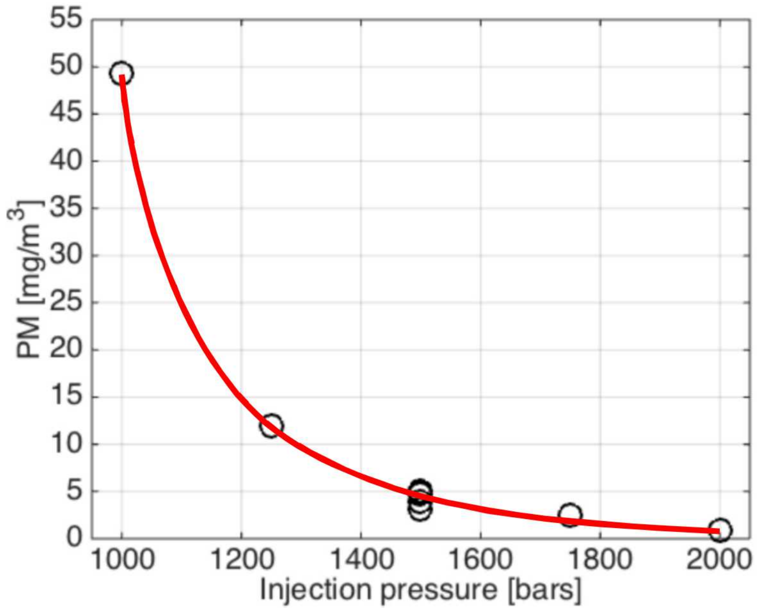
CDC has many advantages & one major disadvantage.

- **Advantages**
  - Inherently high efficiency
  - Easy to control ignition timing by changing fuel-injection timing
  - High torque & power density
  - Durable & reliable
  - Low hydrocarbon (HC) & carbon monoxide (CO) emissions
  - Low cyclic variability
  - Fuel flexible
- **Primary disadvantage: The "soot/NO_x tradeoff"**

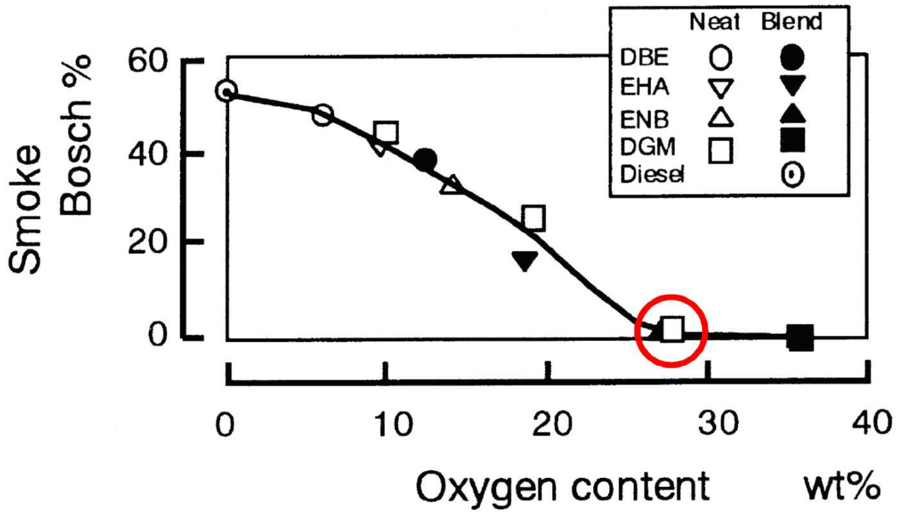


d'Ambrosio and Ferrari, doi:10.1115/1.4005991

Increased injection pressures (P_{inj}) and oxygenated fuels are effective approaches for lowering soot emissions from mixing-controlled CI (i.e., diesel) engines.



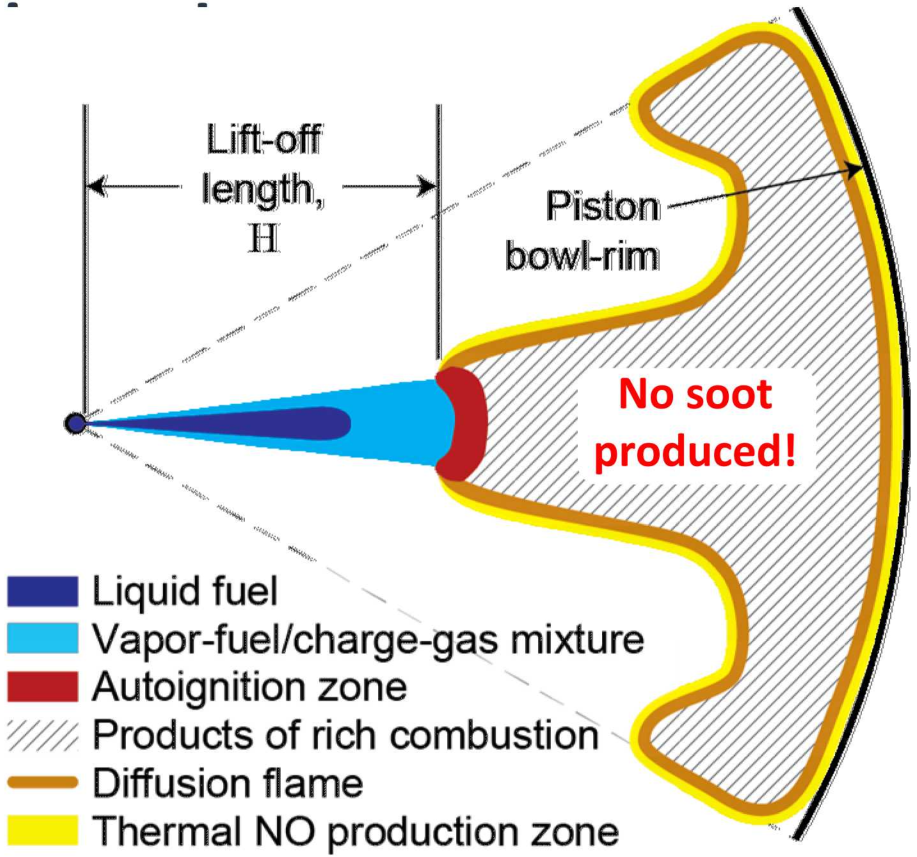
Gallo et al., *SAE Int. J. Engines* **9**(4):2044-55, 2016.



Miyamoto et al., *Int'l J. Engine Res.* **1**(1):71-85, 2000.

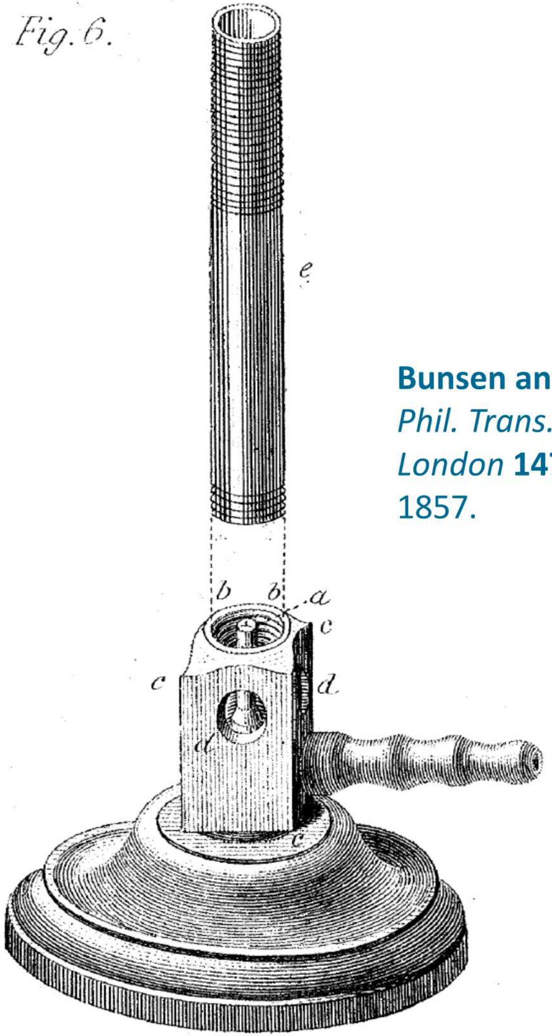
High P_{inj} and oxygenated fuel can be combined to yield MCCI combustion that doesn

- **Leaner lifted-flame combustion (LLFC)**
  - Is MCCI combustion that doesn't form soot because the autoigniting mixture is too fuel-lean
  - Requires a lower equivalence ratio (ϕ) at the liftoff length (H)
    - Threshold level depends on fuel
  - Conservatively, $\phi(H) < 2$
- **High-load, sustained LLFC requires excessive fuel oxygenation (> 50 vol% oxygenate) and/or P_{inj} > 240 MPa**
  - An improved approach is necessary!



Ducted fuel injection (DFI) can further improve mixture formation in the autoignition zone.

- **Simple, mechanical approach**
  - Motivated by Bunsen burner concept

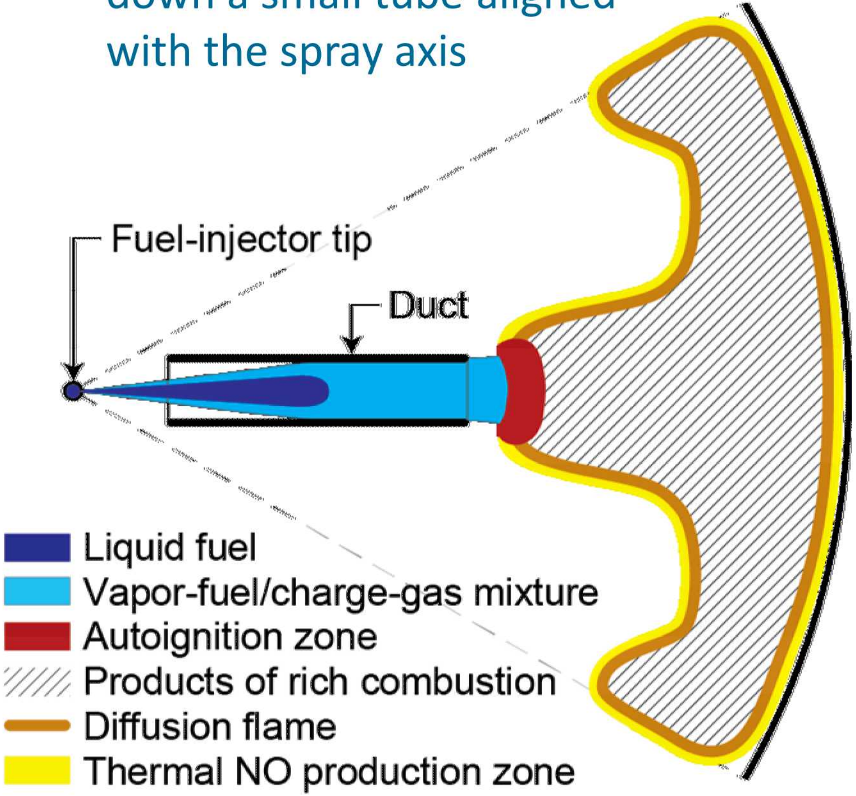


Bunsen and Roscoe, *Phil. Trans. Royal Soc. London* **147**:355-380, 1857.

Ducted fuel injection (DFI) can further improve mixture formation in the autoignition zone.

- **Simple, mechanical approach**
  - Motivated by Bunsen burner concept
  - Modifies mixture, thermal, & velocity fields
- **Effective at eliminating soot**
  - Achieves LLFC over a range of conditions
- **Tolerant to dilution for cost-effective NO_x control**
- **Tolerant to a wide variety of fuels**
  - Doesn’t require oxygenated fuel, but oxygenation further curtails soot production & enlarges viable LLFC range

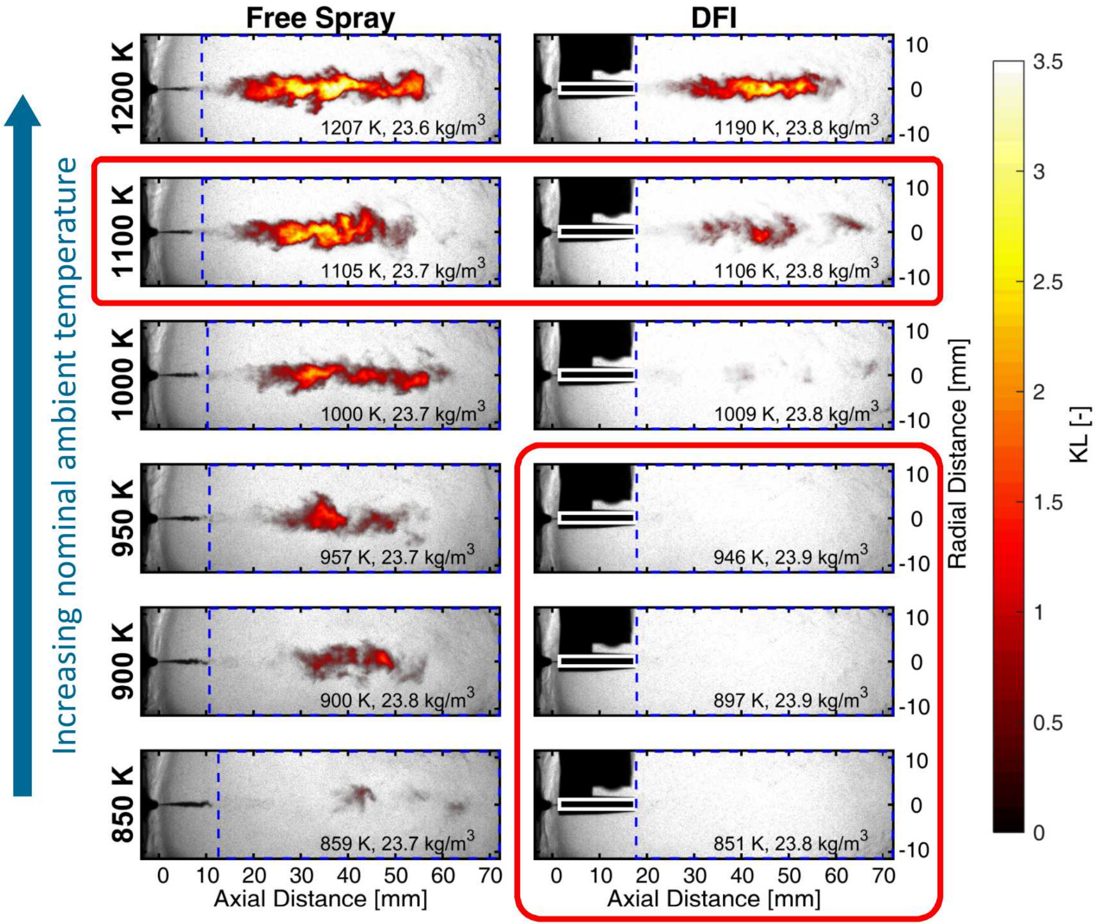
Basic idea: inject the fuel spray down a small tube aligned with the spray axis



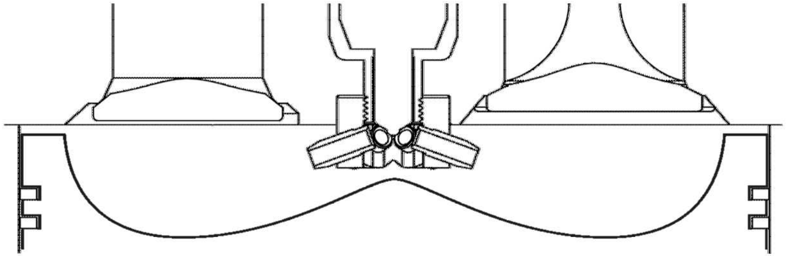
Mueller et al., doi:10.1016/j.apenergy.2017.07.001

DFI curtails or eliminates soot production.

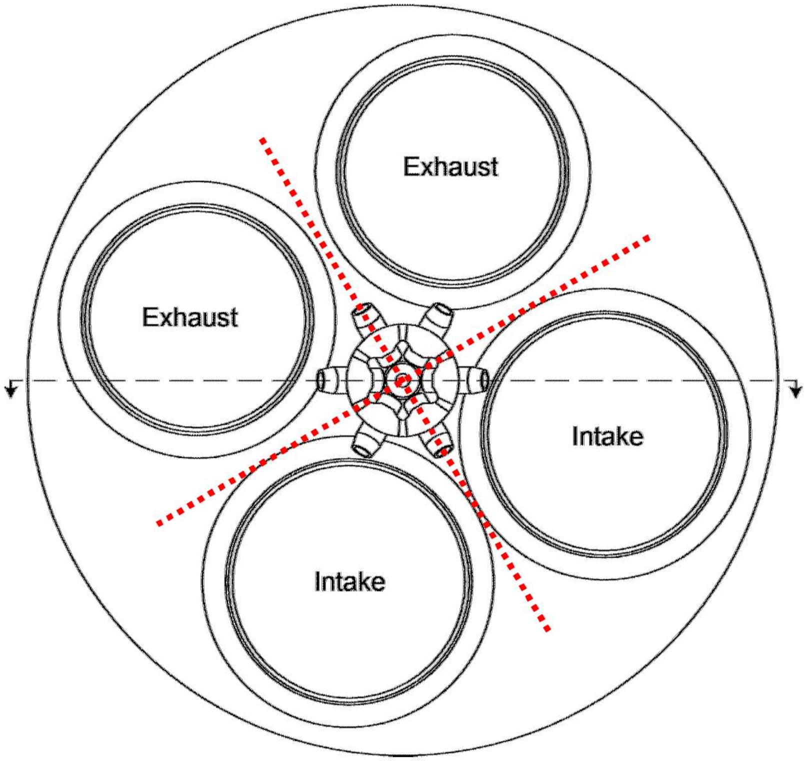
- **Initial experiments conducted in constant-volume combustion vessel**
  - n-dodecane fuel
- **Soot levels are clearly lower with DFI**
  - No soot for T ≤ 950 K
  - Substantial attenuation for T > 950 K
- **That's great, but can DFI work in an engine?**



A possible engine implementation:

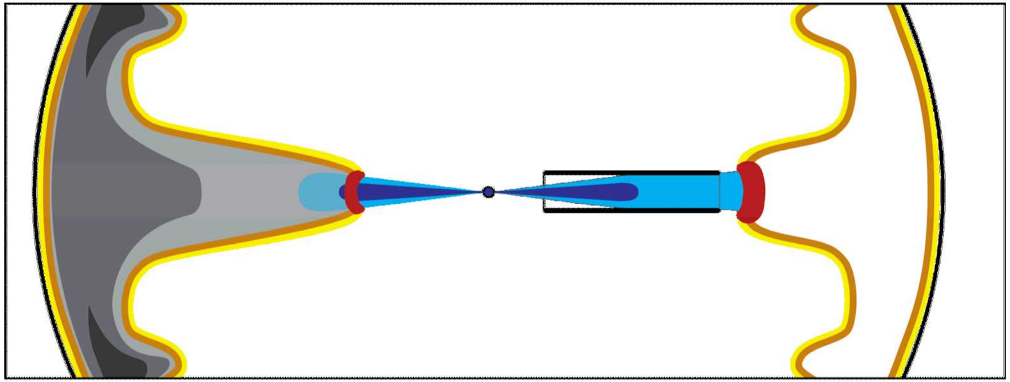


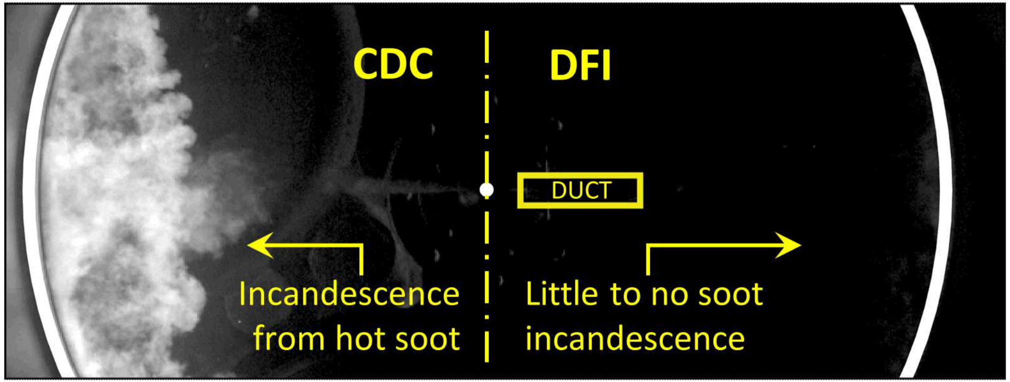
- **Ducts of sufficient length can fit within an engine (125-mm bore)**
  - 12-mm-long ducts aren’t hit by actuating valves
  - Four longer ducts could be used if aligned between valves



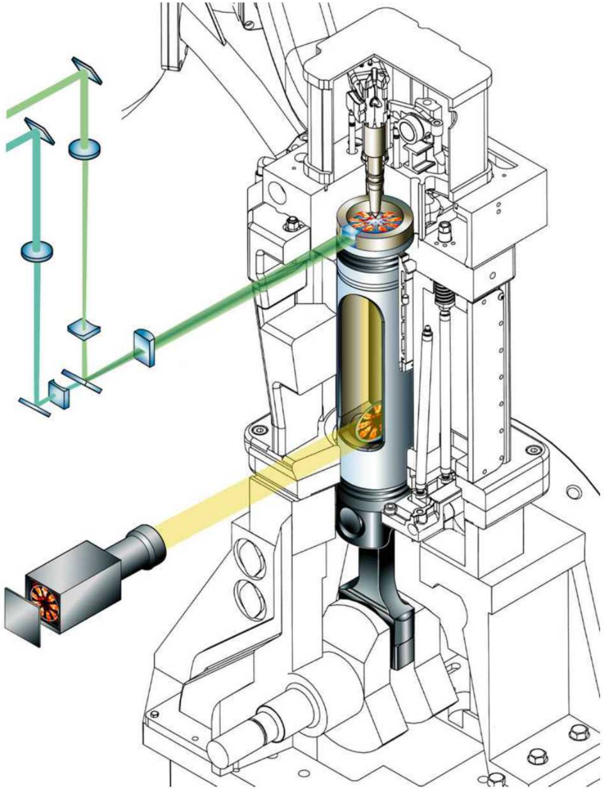
An actual engine implementation:

- **Ducts of sufficient length can fit within an engine (125-mm bore)**
  - 12-mm-long ducts aren't hit by actuating valves
  - Four longer ducts could be used if aligned between valves
- **We have successfully tested DFI in the optical engine with one & two ducts**
  - See presentation by Christopher Nilsen, SAE WCX19, PFL220, April 10, 2019 @ 10:00 am





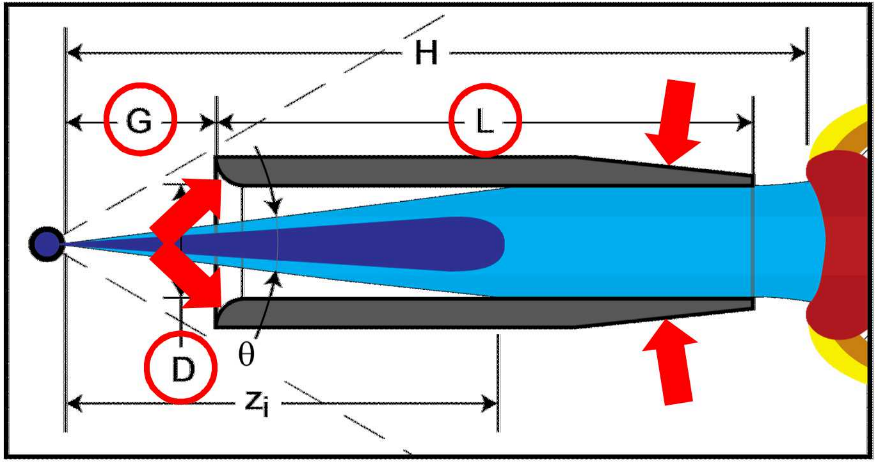
Optical engine specifications & diagnostics

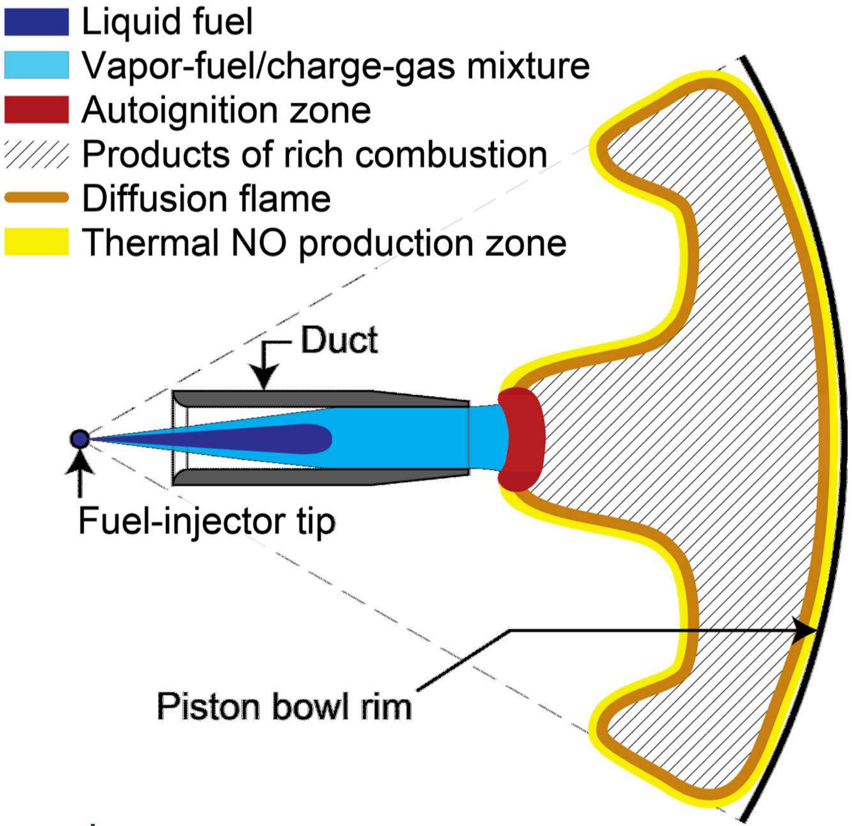


Research engine	Single-cyl.
Cycle	4-stroke CI
Valves per cylinder	4
Bore	125 mm
Stroke	140 mm
Displacement per cylinder	1.72 liters
Conn. rod length	225 mm
Conn. rod offset	None
Piston bowl diameter	90 mm
Piston bowl depth	16.4 mm
Squish height	1.5 mm
Swirl ratio	0.59
Compression ratio	12.5:1
Simulated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

- **Cylinder pressure**
  - App. heat-release rate
  - Bulk and core temp's
- **Engine-out emissions**
  - Smoke, NO_x, HC, CO, O_2, CO_2
- **Fuel injection**
  - Mass and rate
- **Natural luminosity**
  - A sensitive indicator of the presence & distrib'n of hot, in-cylinder soot

Duct configuration

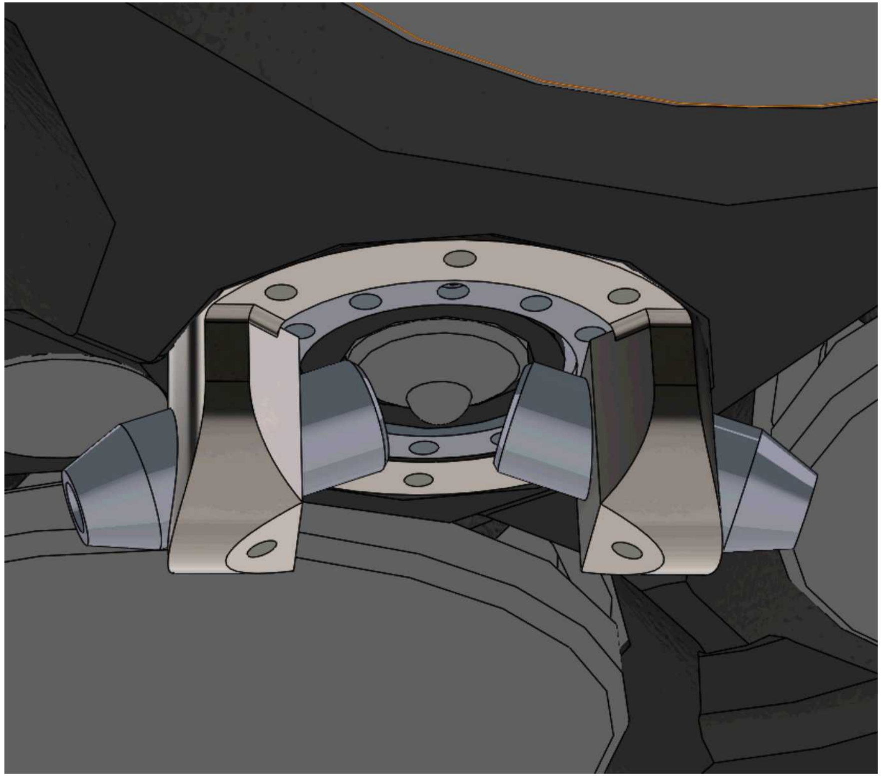




- **Key duct parameters** D2L12
  - Inner diameter (D [mm])
  - Length (L [mm])
  - Standoff distance (G [mm])
  - Inlet/outlet shape (Greek letter)

Conditions for "Engine DFI" experiments

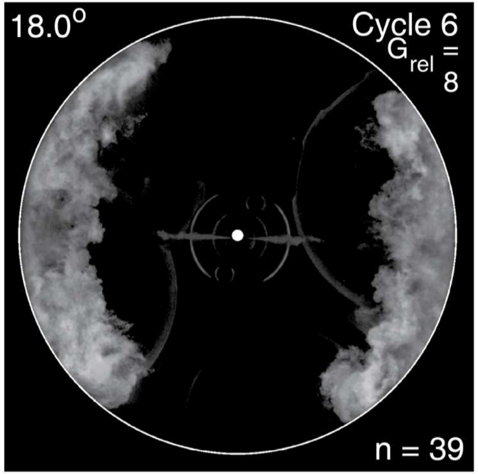
Duct configuration	**D2L12G3δ** or none
Fuel	**No. 2 S15 diesel**
Intake O_2 mole fract's	**21%, 16%**
Engine speed	1200 rpm
Load (gross IMEP)	~2.5 bar
Injector tip	2 × 0.108 mm × 140°
Injection pressure	180 MPa
Injection schedule	Single inject'n, 3.5 ms
Start of combustion	TDC (= 0 CAD)
Intake pressure (abs.)	2.00 bar
Intake temperature	90 °C
Coolant temperature	90 °C

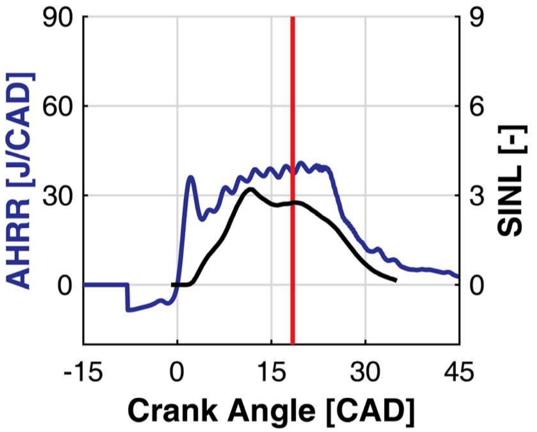


Engine results: Natural luminosity movies

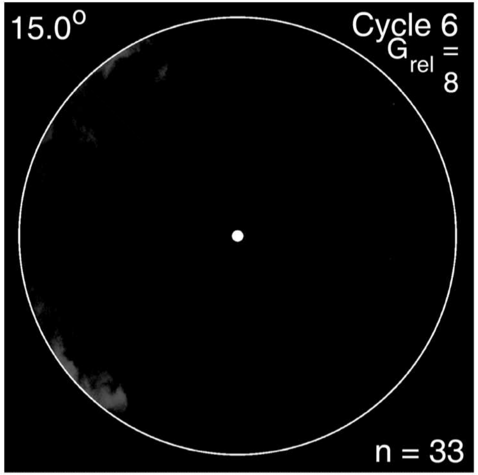
- **Data acq’d at 16 mol% O_2 in intake mixture**
- **DFI almost completely eliminates incandescence from hot soot**
- **LLFC nearly achieved**
  - With No. 2 diesel fuel
  - At low-NO_x conditions that would normally lead to unacceptable soot levels

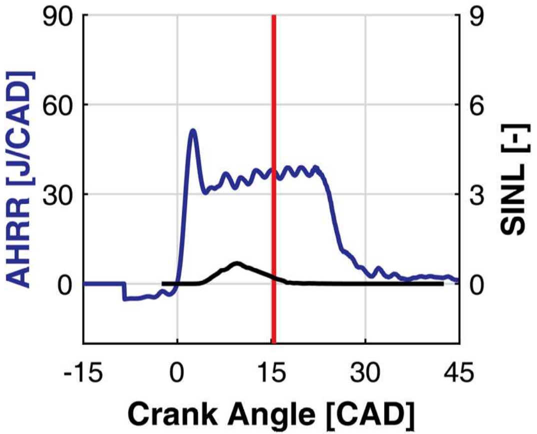
CDC





DFI

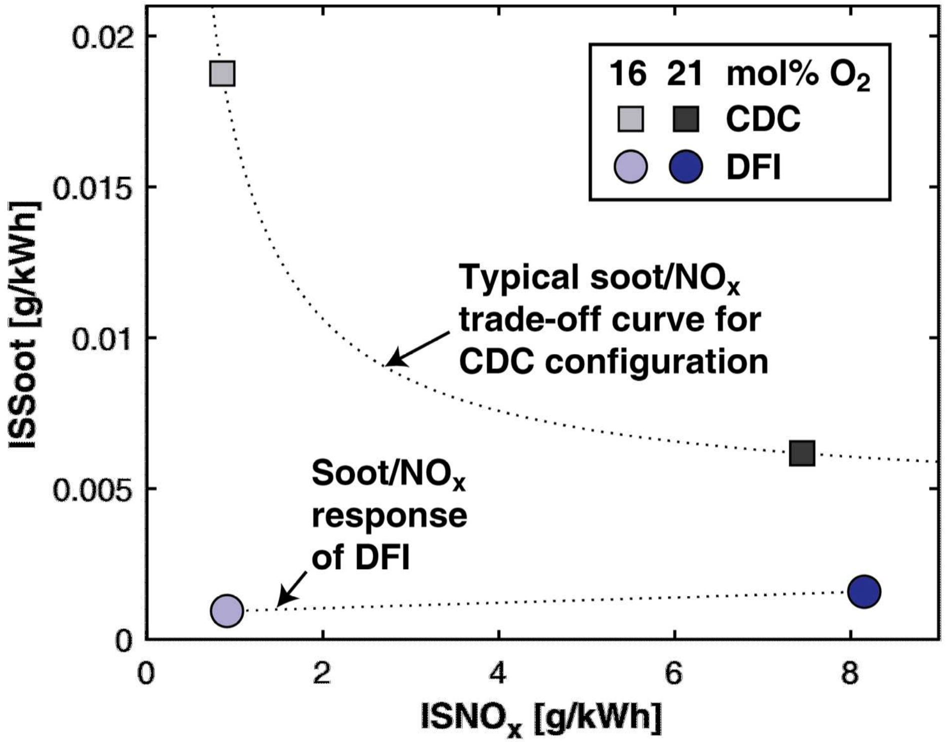




AHRR = apparent heat-release rate; SINL = spatially integrated natural luminosity; CAD = crank angle degree

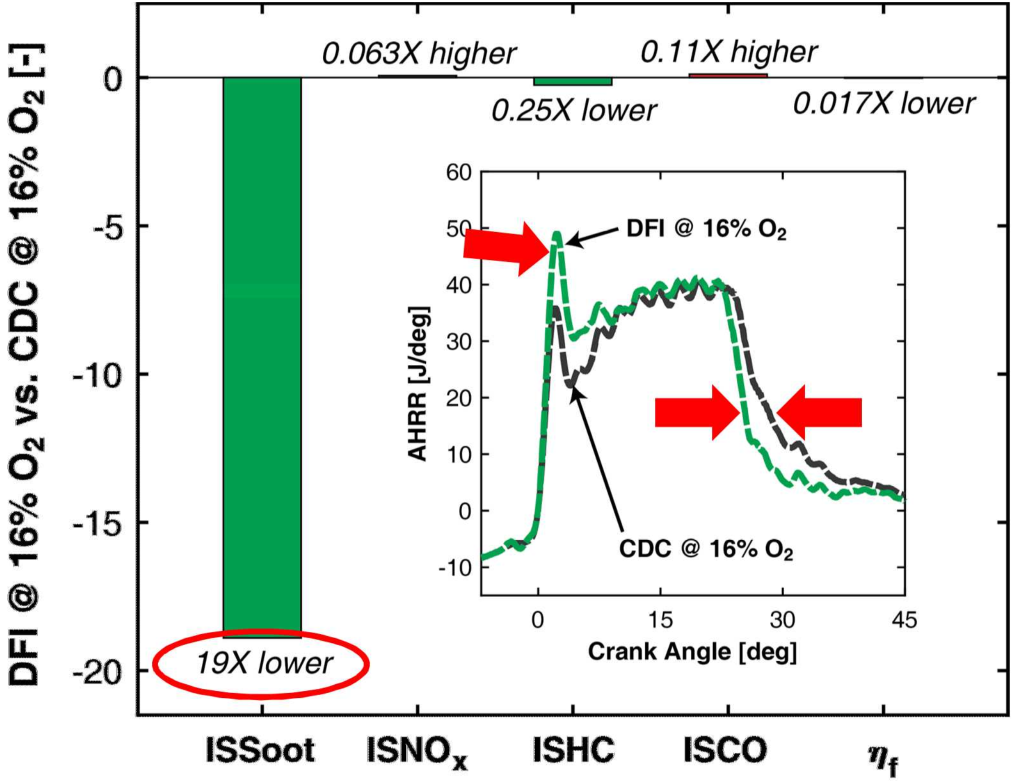
Engine results: DFI with dilution can break the long-standing diesel soot/NO_x trade-off.

- **Points show measured data**
- **DFI with dilution lowers soot & NO_x emissions simultaneously**
  - Unclear where the dilution benefit ends
  - Oxygenated fuels provide even larger benefits
- **This is great, but what are the effects on other emissions, efficiency, and heat release?**



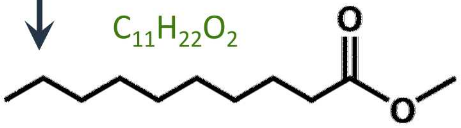
DFI vs. CDC at moderate dilution: Soot is dramatically attenuated with DFI, other changes are relatively small.

- **DFI attenuates engine-out soot by more than an order of magnitude**
  - Changes in other emissions & fuel-conversion efficiency (η_f) are small
- **Heat release (inset): DFI has**
  - Larger premixed-burn spike
    - ↑ in combustion noise
  - Shorter burn duration

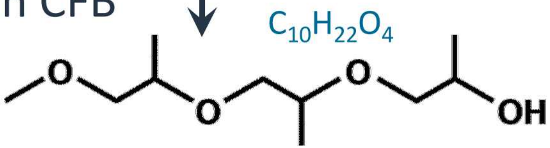


Fuels & operating conditions for Co-Optima study showing additional benefits from oxygenated fuels

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



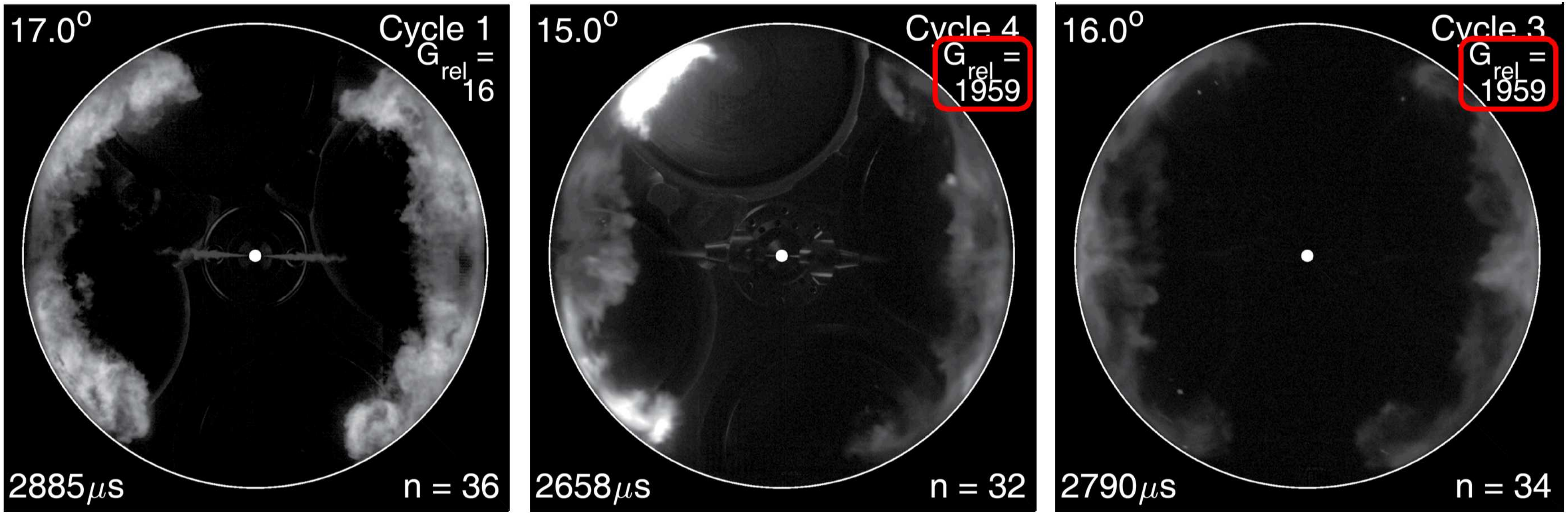
  - **T25** = 25 vol% tri-propylene glycol mono-methyl ether in CFB



Fuels	**CFB**, **MD25**, **T25**
Intake O_2 mole fractions	**21%, 16%**
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. pressure	2.00 bar
Intake manifold temperature	90 °C
Coolant temperature	90 °C

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

CFB CDC @ 16 mol% O_2 | MD25 DFI @ 16 mol% O_2 | T25 DFI @ 16 mol% O_2



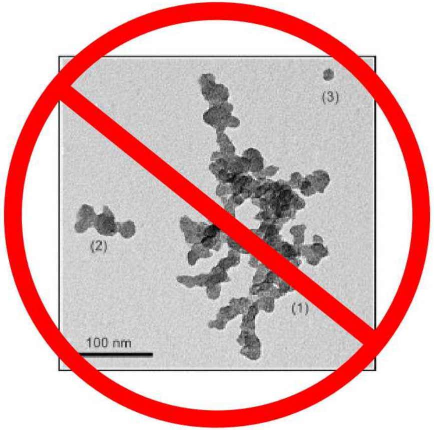
Status quo: Significant engine-out soot

Transition: "Zero" engine-out soot

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

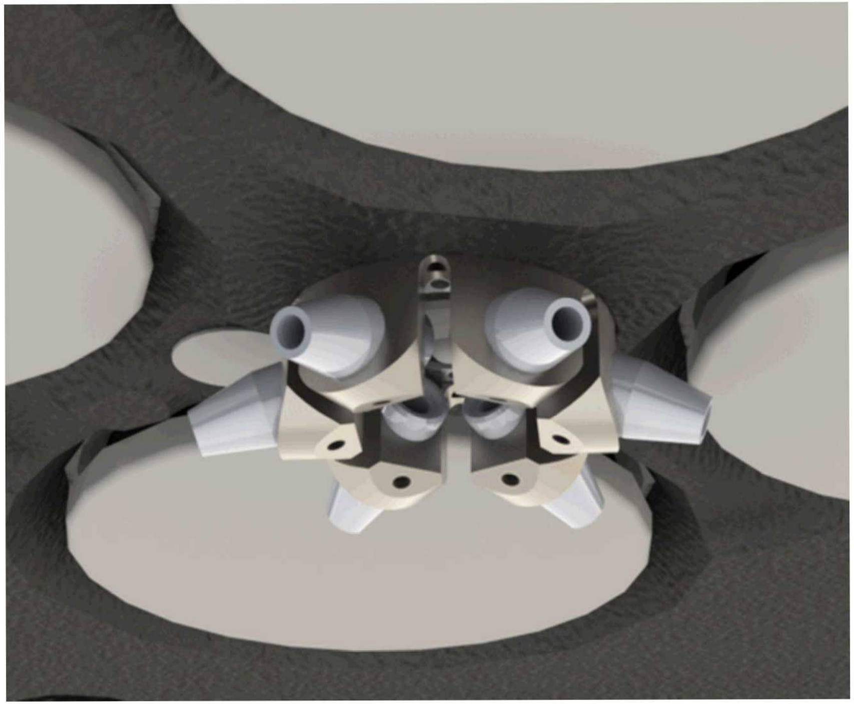
DFI could facilitate the implementation of clean, sustainable heavy- and medium-duty engines and fuels.

- **Vision: Evolve from CDC to LLFC enabled by DFI & sustainable, synergistic fuels**
  - Inherently high & potentially improved efficiency
  - Compatible with current diesel fuels → no "chicken & egg" problem
  - Synergistic with potential future diesel fuels
    - Renewable blendstocks can be added per policy & economics
    - Oxygenates enable even lower soot, providing market "pull"
  - Lower emissions → smaller/less-costly aftertreatment
  - Easy to control & conceptually simple
  - Retrofittable → near-term benefits for existing (large) engines
  - Scientifically distinct: a different set of trade-offs relative to globally premixed combustion strategies provides stakeholders a complementary technology path



Potential challenges with DFI

- **Combustion noise**
- **Scaling up to more ducts**
- **Hardware implementation**
  - Achieving initial spray/duct alignment
  - Ensuring long-term spray/duct alignment
- **Durability**
  - Deposit formation
  - Thermal fatigue
- **Cold-start performance**
- **Efficiency: combustion, thermal**
- **Cyclic variability**



Summary

- **MCCI combustion is highly desirable: efficient, easy to control, fuel tolerant,…**
  - Historical challenge has been emissions compliance due to soot/NO_x tradeoff
  - If soot formation can be prevented, less expensive exhaust-gas recirculation can be used to control NO_x without sacrificing other advantageous MCCI attributes
- **Ducted fuel injection shows promise, but is still in early stages of development**
  - Dramatically lowers engine-out soot emissions
  - Breaks the long-standing soot/NO_x trade-off with dilution
  - Has relatively minor effects on other emissions & efficiency

DFI with dilution & renewable fuels could provide a feasible path to clean, sustainable engines & fuels for the future.

DFI Acknowledgments

- **Christopher W. Nilsen**, Drummond E. Biles, **Boni F. Yraguen**, & Daniel J. Ruth
  - Interns who assisted with data acq. & analysis
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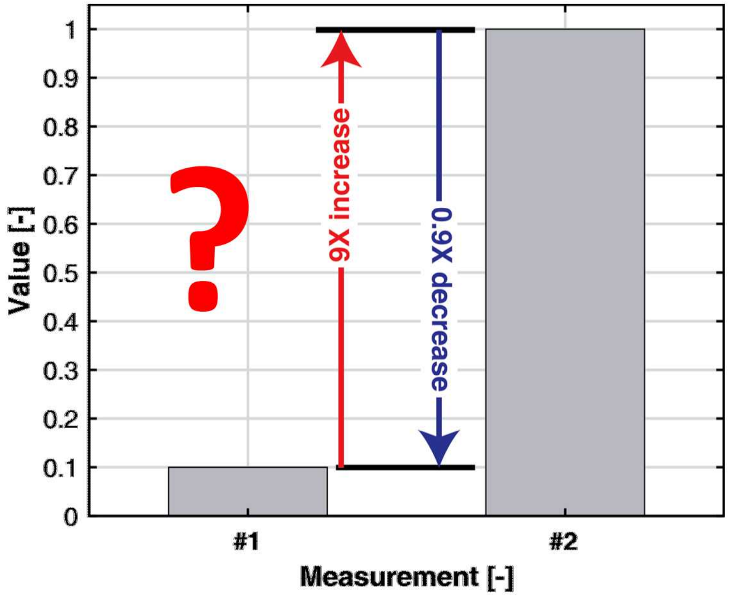
  - Technologists assisting with lab. infrastructure, light sources, electronics, & software

Related DFI research projects

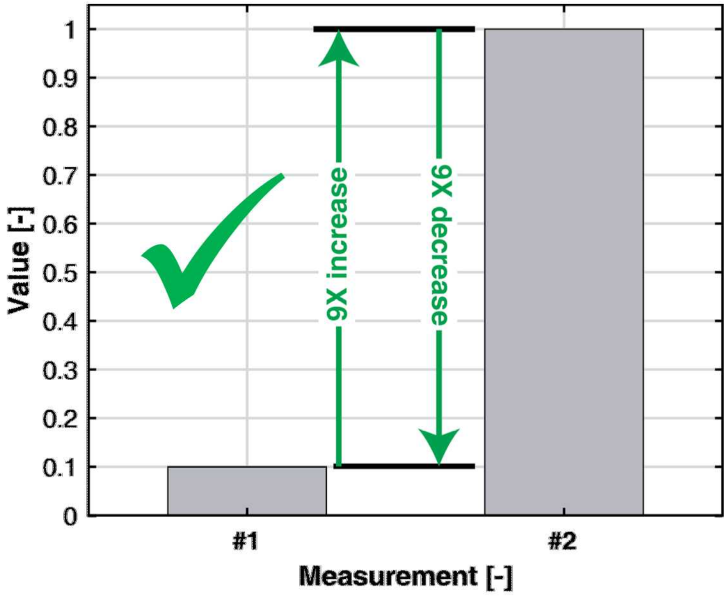
- **DOE Advanced Combustion Engines program**
  - FY19: Engine operating-condition effects on DFI
- **DOE Co-Optimization of Fuels & Engines program ("Co-Optima")**
  - FY19: Oxygenated-fuel effects on DFI
- **DOE Technology Commercialization Fund CRADA with Caterpillar & Ford (2 yrs.)**
  - Overcoming barriers to commercialization of DFI

The difference function enables consistent quantification of change, independent of the observer's perspective.

- **Conventional def'n of change** $\frac{Obs.-Acc.}{Acc.}$
  - Result depends on perspective!



- **Difference function** $\frac{Obs.-Acc.}{min(Obs.,Acc.)}$
  - Result is independent of perspective



Gaps in understanding: Why/how does DFI work?

- **Enhanced mixing/entrainment within &/or downstream of duct**
  - Transient turbulent compressible flow
  - Unknown entrainment at duct entrance and exit
- **Heat transfer**
  - Heat transfer to/from duct
  - Effect of altered entrainment on fuel vaporization
- **Alignment effects**
- **Kinetic effects**
  - Effects of mixing on ignition delay
  - Negative temperature coefficient (NTC) effects
- **Strain rate at duct exit may increase ignition delay**

Curran et al., *Combust. Flame* **114**:149–177, 1998