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Using Ducted Fuel Injection to Attenuate Soot Formation in a Mixing-Controlled Compression-Ignition Engine

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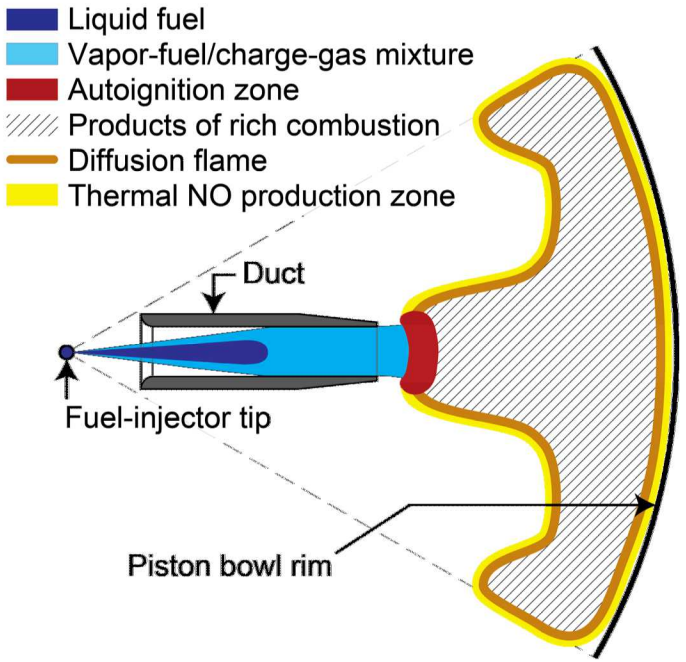
What Is Ducted Fuel Injection (DFI)?

- DFI is…
  - injecting fuel down the axis of one or more small tubes within the combustion chamber
  - to enhance mixture preparation upstream of the autoignition zone

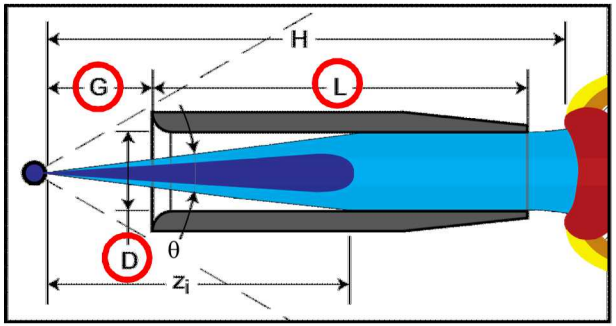
    to curtail soot & other emissions
  - to lower engine cost & improve performance



Key DFI parameters

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

D2L12G3.1δ

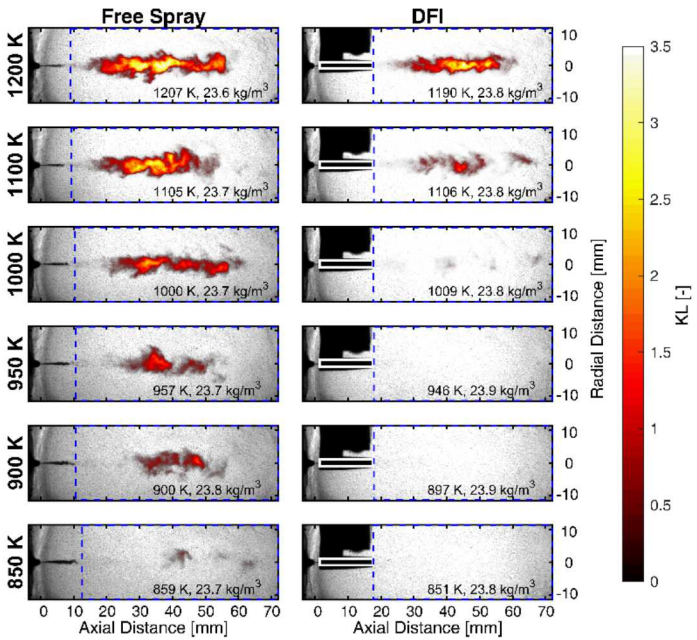


Goals

- Show that DFI works inside of an engine
  - Integrate DFI hardware into an engine
  - Does DFI attenuate engine-out soot?
  - What effect does DFI have on efficiency and other engine-out emissions?
  - How hard is it to align the duct properly?
  - Achieve diesel combustion that doesn't form soot
- Future Goals
  - Develop understanding of how DFI works
    - Mixing
    - Entrainment
    - Temperature

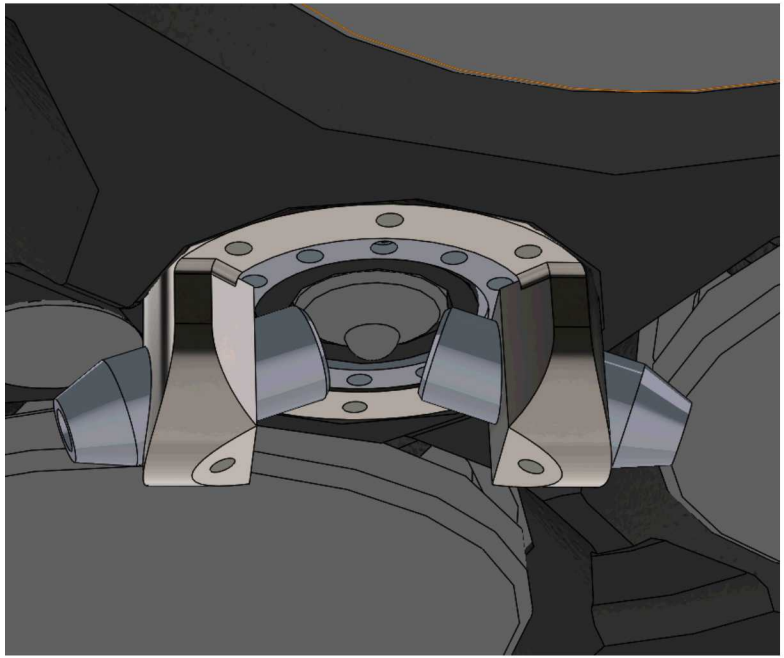
Why does DFI matter?

- Inherently high fuel efficiency of mixing-controlled CI combustion
- Combust'n timing is easy to control by inject'n timing
- Breaks the soot/NO_x tradeoff
  - Lower aftertreatment costs
- Fuel flexible
  - Compatible w/ current diesel fuel
  - Add'l benefits from oxygenated renewable fuels
- Scientifically distinct from globally premixed strategies
  - An alternative/complementary option (less well understood)
  - Potentially easier to control



Overview of "Engine DFI" experiments

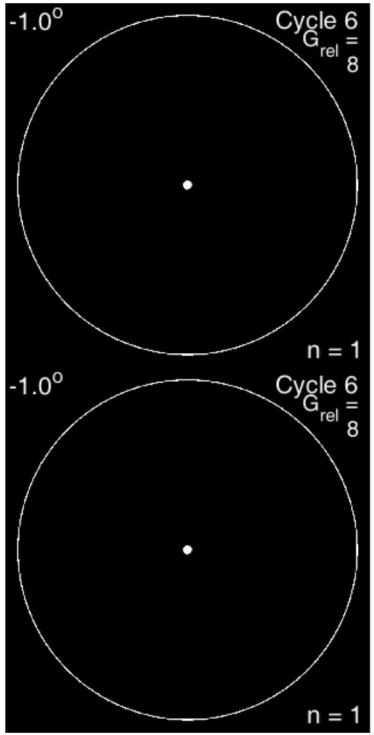
- Test matrix
  - D2L12G1.6δ & D2L12G3δ ducts tested vs. free spray at 16 & 21 mol% O_2
- Stainless-steel duct
- No. 2 S15 diesel cert. fuel (CFA)
  - ~30 wt% aromatics
- Start of combustion (SOC) = TDC
- P_{int} = 2.00 bar, T_{int} = 90 °C
- 110 µm orifice diameter, 2 hole tip, 3.50 ms injection duration at 180 MPa
- 3 replicates for each condition

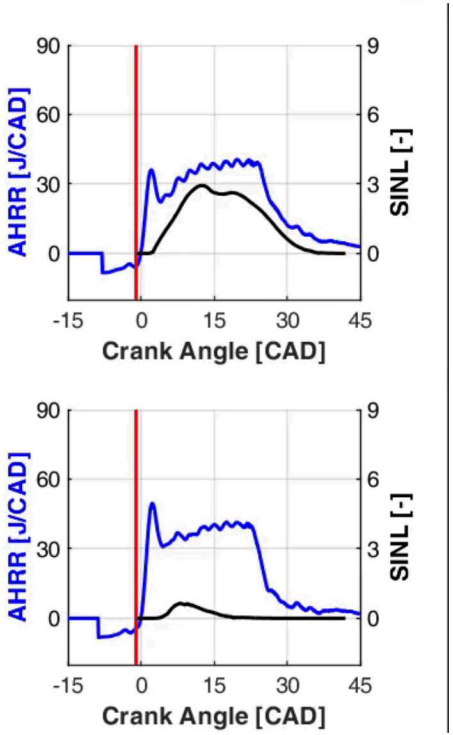


DFI curtails or eliminates soot production at 16% O_2

Free Spray

DFI

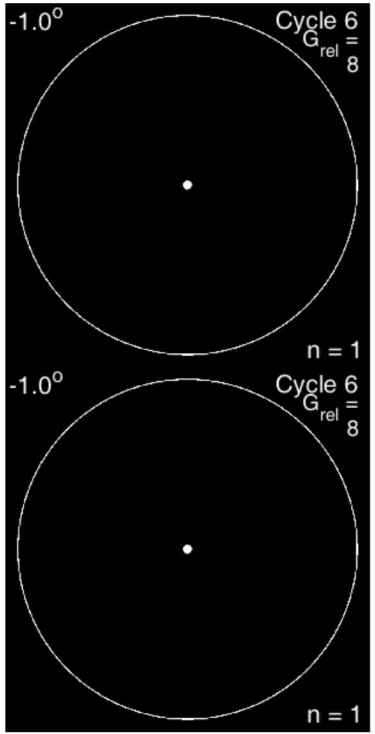


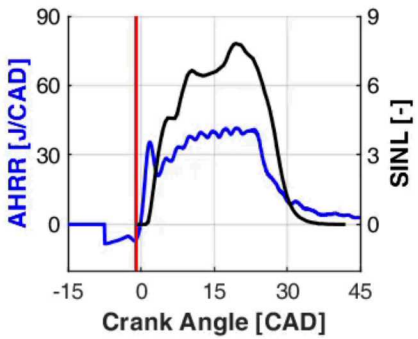


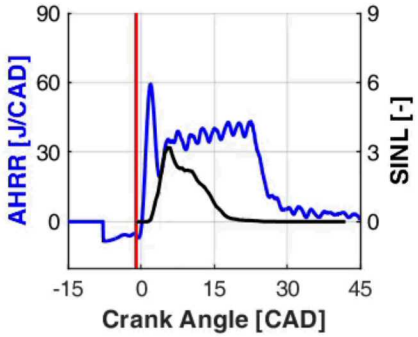
DFI curtails or eliminates soot production at 21% O_2

Free Spray

DFI

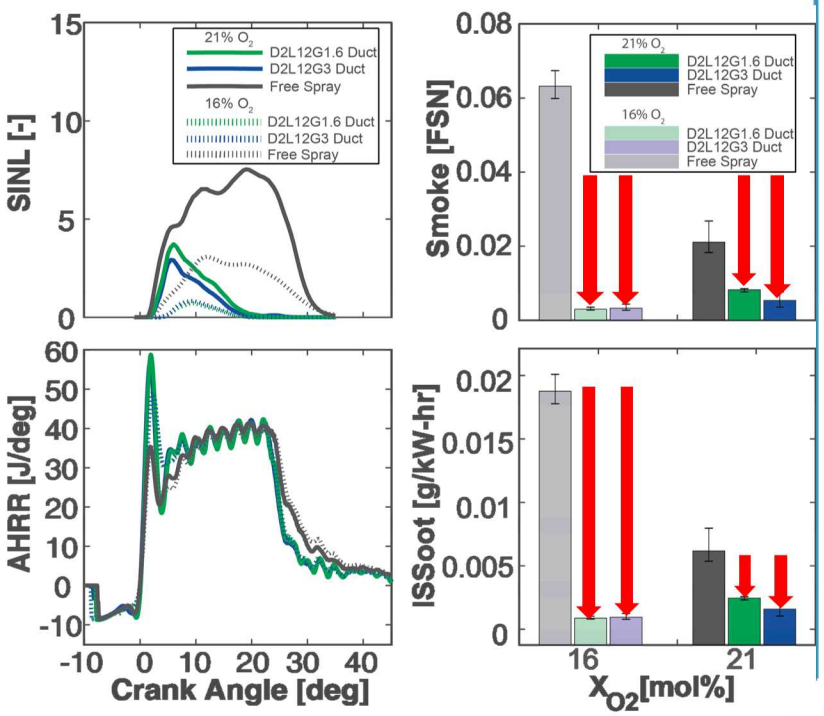






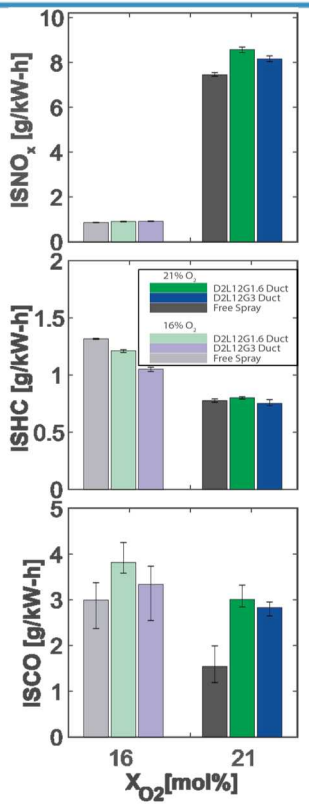
DFI consistently attenuates soot

- Peak SINL is reduced significantly
  - ~50% reduction at 21%O_2
  - ~75% reduction at 16% O_2
- Integrated SINL is reduced by even more
  - ~80% reduction at 21% O_2
  - ~90% reduction at 16% O_2
- AVL Filter Smoke Number (FSN) is lower
  - 57% reduction in FSN at 21% O_2
  - 95% reduction in FSN at 16% O_2
- Soot emissions (ISSoot) are attenuated
  - 58% lower soot at 21% O_2
  - 96% lower soot at 16% O_2



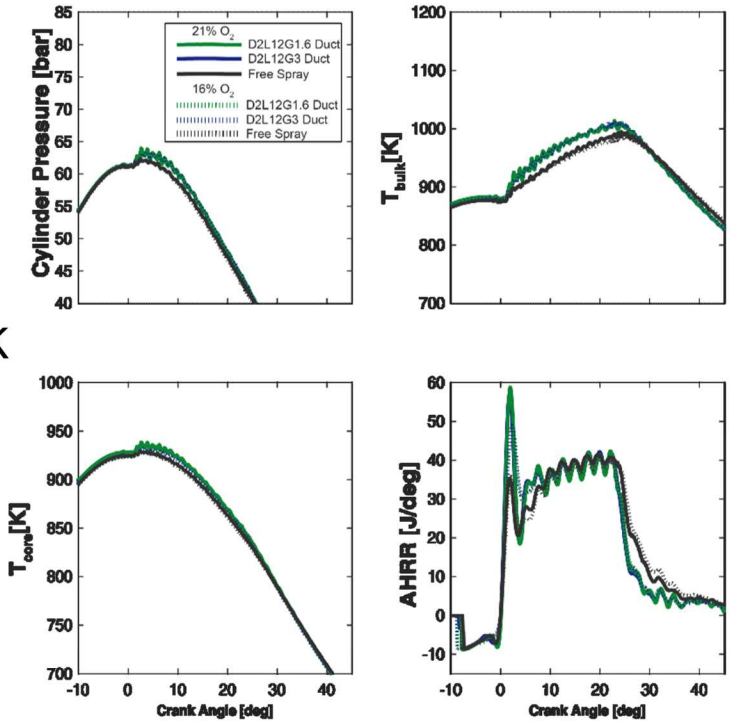
What effect does DFI have on other engine-out emissions?

- General emissions trends with changing dilution are the same for DFI vs. free-spray combustion
- NO_x emissions are higher for DFI at 21% O_2
- HC emissions are somewhat lower for DFI at 16% O_2
- CO emissions are somewhat higher
  - CO meter does not give particularly stable results



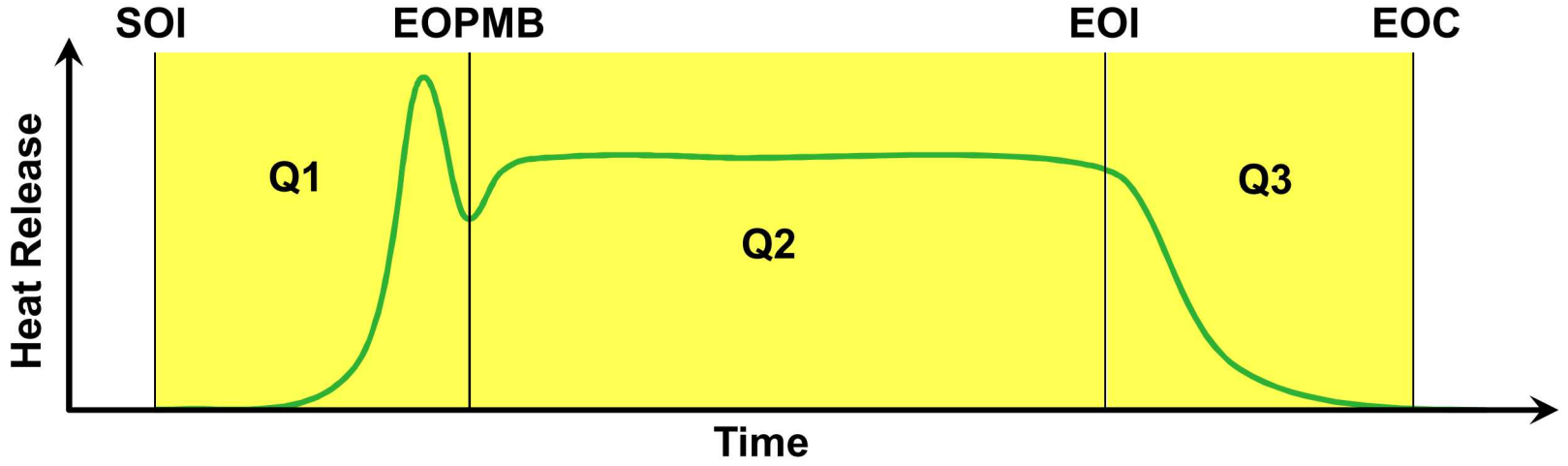
Effects of DFI on pressure, temperature, & AHHR

- DFI creates a larger premixed burn spike
  - This creates higher peak pressures & temperatures
  - Peak pressure is increased by ~3 bar at 21% O_2 & ~2 bar at 16% O_2
  - Peak temperature is increased by ~1.5 K at 21% O_2 & ~3 K at 16% O_2
- DFI AHRR has “square wave” profile
  - It has sharp initial rise, reaches steady state quickly, & ends quickly



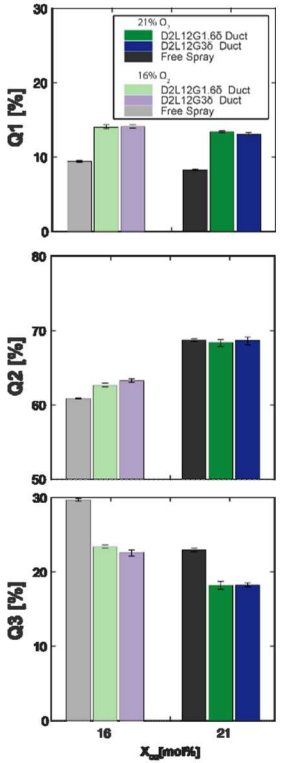
Three stages of mixing-controlled compression-ignition (MCCI) combustion

1. From start of injection (SOI) to end of premixed burn (EOPMB)
2. During quasi-steady phase of mixing-controlled combustion
3. From end of injection (EOI) to end of combustion (EOC)



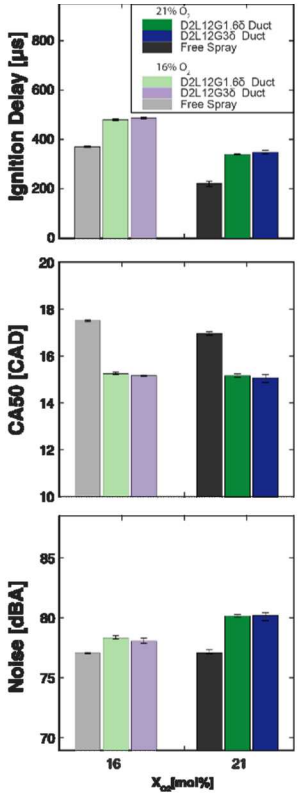
Effect of DFI combustion distribution

- Q1% is higher for DFI
  - This indicates that more fuel is burned in the premixed burn phase
- Q2% is very similar for DFI
  - This indicates that the amount of fuel burned in the mixing controlled combustion stage is similar
- Q3% is lower for DFI
  - DFI ends combustion more quickly after EOI



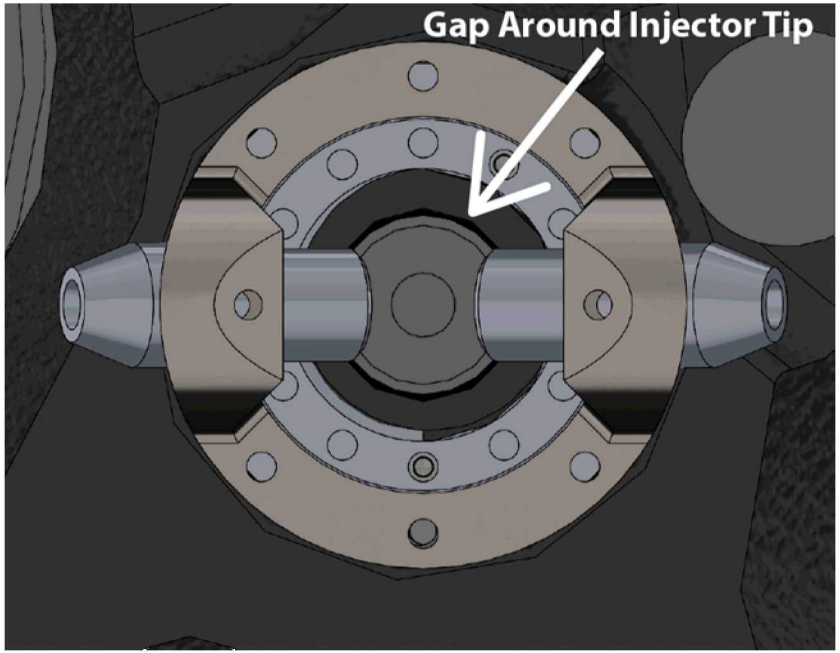
DFI stability & noise

- Ignition delay is longer for DFI at both 16% O_2 & 21% O_2
- The ignition delay for each case is stable
- CA50 is ~2 CAD earlier for DFI. This may explain the increase in NO_x observed with DFI
- The combustion noise for DFI is higher
  - 3 dB higher at 21% O_2
  - 1 dB higher at 16% O_2
  - Still well below “Light-Duty Noise Guidelines for Advanced Combustion Research” from USDRIVE ACEC Technical Team



Design issues with DFI

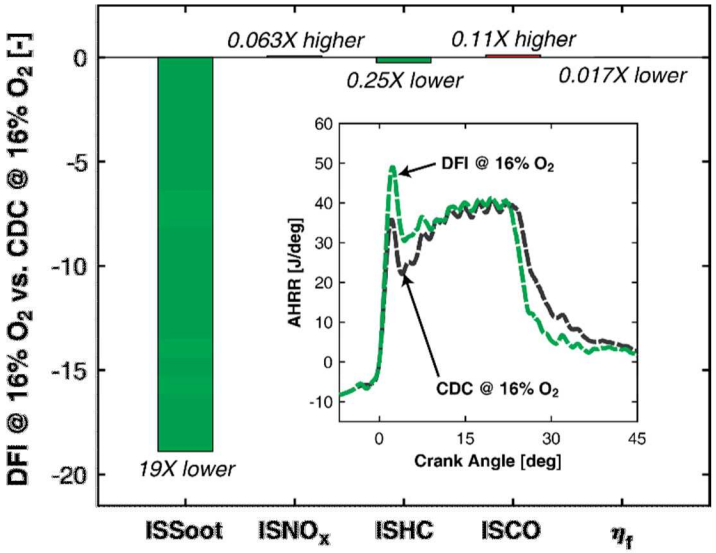
- Duct alignment
  - Alignment has to be set axially as well as rotationally
  - Goal for alignment is spray to enter duct within ±0.001” of the center
- Injector alignment
  - Injector should be designed to be tightly centered inside of cylinder
  - Shims are currently being used to center injector in sleeve



DFI vs. Conventional Diesel Combustion (CDC) with dilution

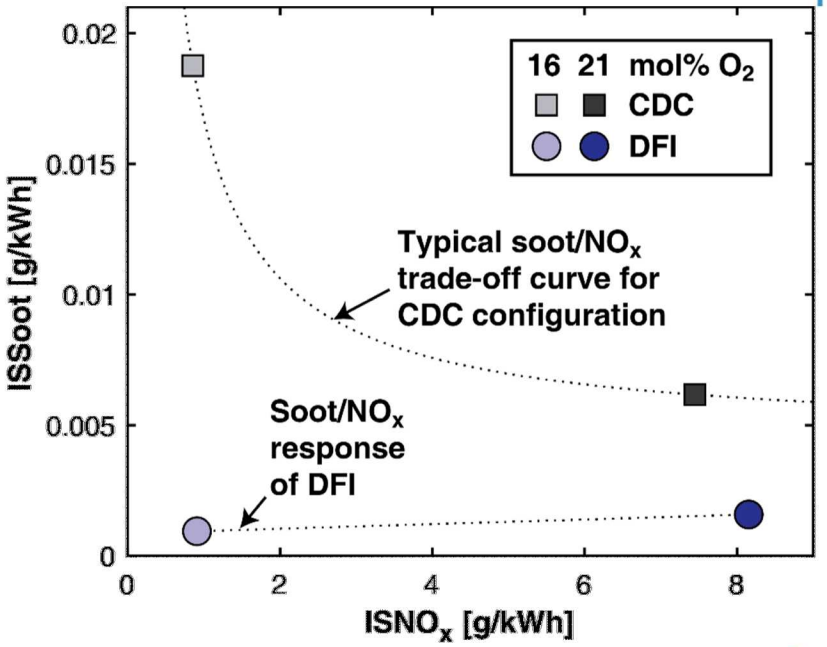
- DFI attenuates soot by more than an order of magnitude
  - Other emissions & efficiency are nearly unchanged
  - Peak pressure is increased by ~3 bar at 21% O_2 & ~2 bar at 16% O_2
  - Higher peak AHRR & shorter combustion duration

    “Square wave” AHRR profile



DFI with dilution can break the diesel soot/NO_x trade-off

- DFI with dilution lowers soot & NO_x emissions simultaneously
  - Unclear where the dilution benefit ends
  - Oxygenated fuels are likely to provide even larger benefits



Conclusion

- DFI is effective at attenuating engine-out soot emissions from an MCCI engine
- DFI has been observed to break the soot/NO_x tradeoff
  - Its performance is improved by increasing dilution!
- The duct assembly can be made small enough to be installed in an engine & can be aligned without the use of specialized tooling

Thank you!

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