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Ducted Fuel Injection vs. Conventional Diesel Combustion: An Operating-Parameter Sensitivity Study Conducted in an Optical Engine with a Four-Orifice Fuel Injector

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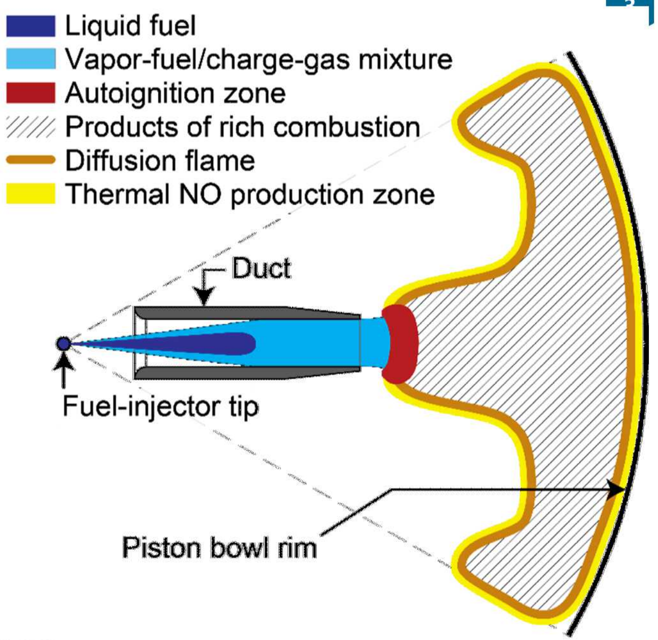
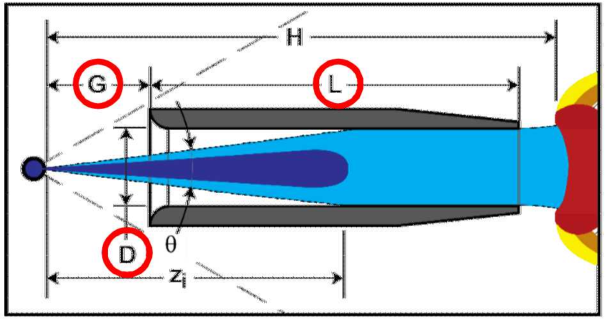
Abstract

Ducted fuel injection (DFI) has been shown to attenuate engine-out soot emissions from diesel engines. The concept is to inject fuel through a small tube within the combustion chamber to enable lower equivalence ratios at the autoignition zone, relative to conventional diesel combustion (CDC). Previous experiments have demonstrated that DFI enables significant soot attenuation relative to CDC for a small set of operating conditions at relatively low engine loads. This is the first study to compare DFI to CDC over a wide range of operating conditions and at higher loads (up to 8.5 bar gross indicated mean effective pressure) with a four-orifice fuel injector. This study compares DFI to CDC through sweeps of intake-oxygen mole fraction, injection duration, intake pressure, start of combustion timing, fuel-injection pressure, and intake temperature. DFI is shown to curtail engine-out soot emissions at all tested conditions. Under certain conditions, DFI can attenuate engine-out soot by over 100X. In addition to producing significantly lower engine-out soot emissions, DFI enables the engine to be operated at low-NOx conditions that are not feasible with CDC due to high soot emissions.

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 and other emissions
  - to lower engine system cost and improve performance
- **Key DFI parameters** — **D2L12G3.0δ**
  - Inner diameter (D [mm])
  - Length (L [mm])
  - Standoff distance (G [mm])
  - Inlet/outlet shape (Greek letter)

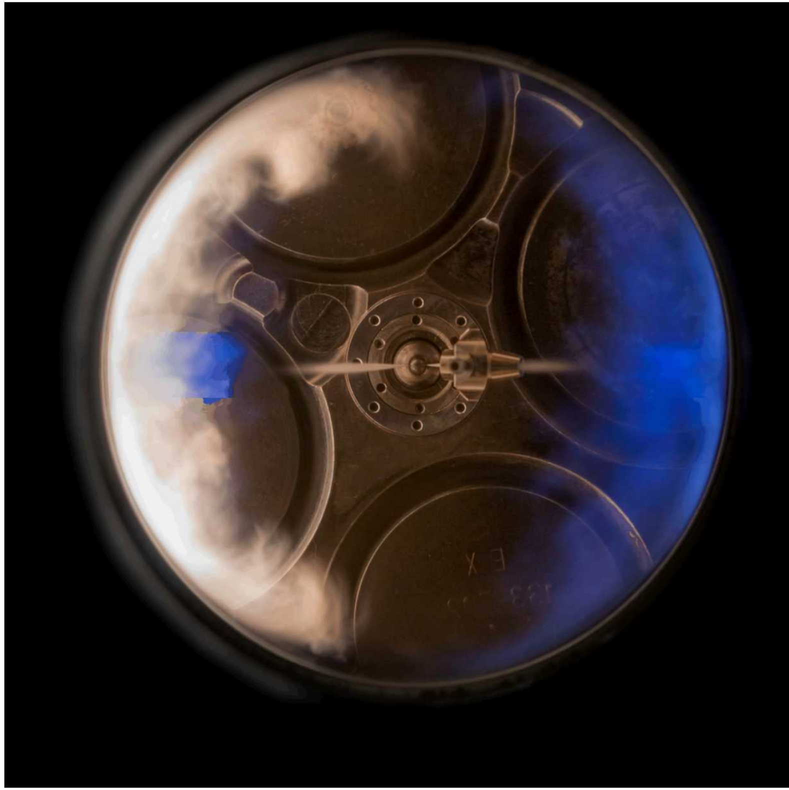


Goals

- **Show that DFI works inside of an engine**
  - Test DFI across a wide range of conditions
  - Does DFI attenuate engine-out soot across an entire parameter sweep?
  - What effect does DFI have on other engine-out emissions and efficiency, and how do these effects vary with operating parameters?

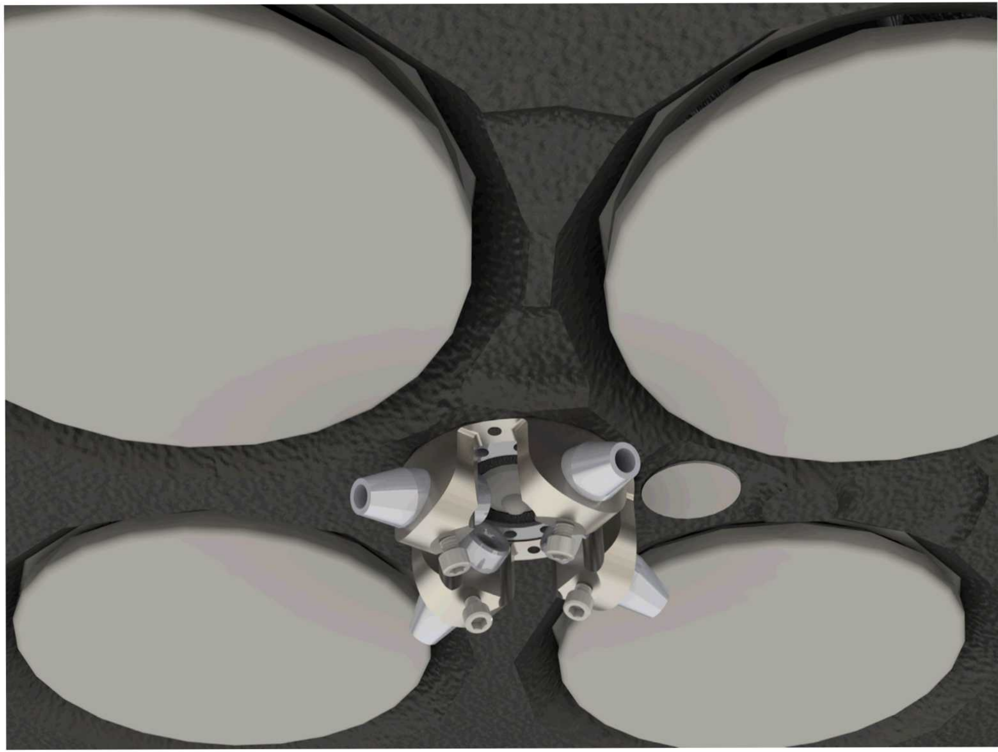
Why does DFI matter?

- **Inherently high fuel efficiency of mixing-controlled CI combustion**
- **Combustion timing is easy to control by injection 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" experimental baseline

Experimental Conditions	
Fuel	No. 2 S15 diesel cert. fuel CFB
Speed	1200 rpm
Duration of injection	3500µs
Injection pressure	180 MPa
Injector tip configuration	4 × .110 mm × 140°
Ducts	4D2L12G3δ vs. none
Start of combustion timing	0.0 CAD ATDC
Dilution	16 mol% O_2
Intake manifold pressure	2.5bar
Intake manifold temperature	90 °C
Coolant temperature	90 °C



“Engine DFI” parameter sweep

21 mol%					
18 mol%	4500 μs	+5° ATDC	240 MPa	3.00 bar	
XO_2 = 16 mol%;	DOI_i = 3500 μs;	SOC = 0° ATDC;	P_{inj} = 180 MPa;	IMAP = 2.50 bar;	IMT = 90 °C
14 mol%	2500 μs	-5° ATDC	80 MPa	2.00 bar	70 °C
12 mol%	1500 μs				50 °C

IMAP correction

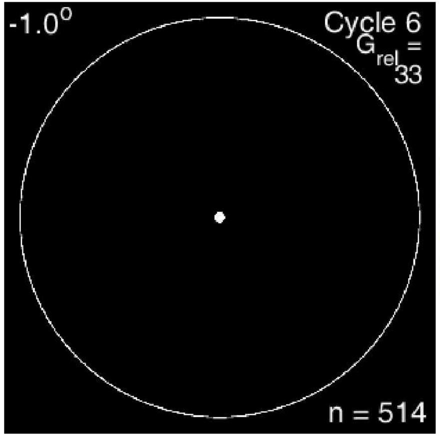
- The optical engine has a 12.5:1 compression ratio compared to 16.5:1 in a typical modern diesel
- Match TDC conditions assuming isentropic compression

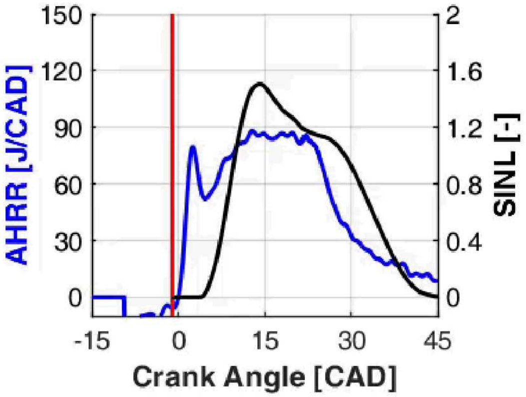
$$\frac{p_1}{p_2} = \left(\frac{V_2}{V_1}\right)^k = \left(\frac{T_1}{T_2}\right)^{\frac{k}{k-1}}$$

Pressure		Temperature	
12.5:1	16.5:1	12.5:1	16.5:1
2.0 bar	1.25 bar	50 °C	9 °C
2.5 bar	1.55 bar	70 °C	27 °C
3.0 bar	1.86 bar	90 °C	44 °C

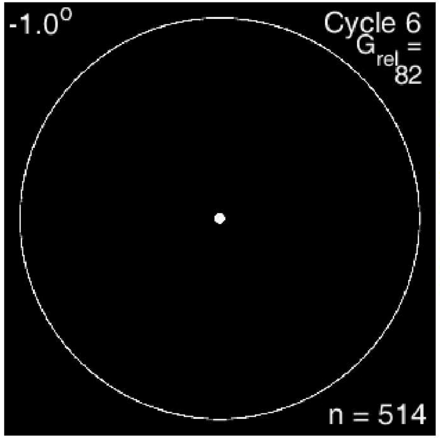
Dilution sweep (NL movies 12 mol% O_2)

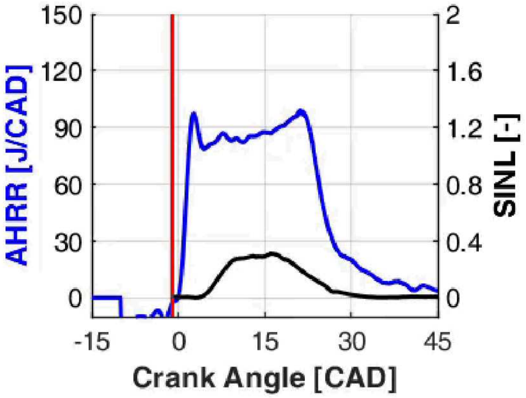
CDC





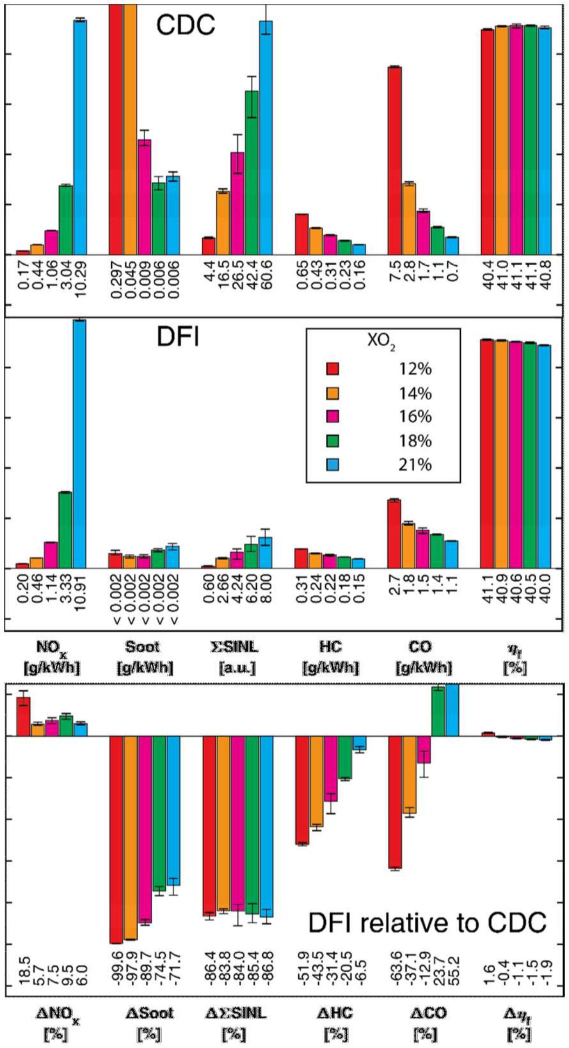
DFI





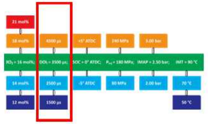
Dilution sweep

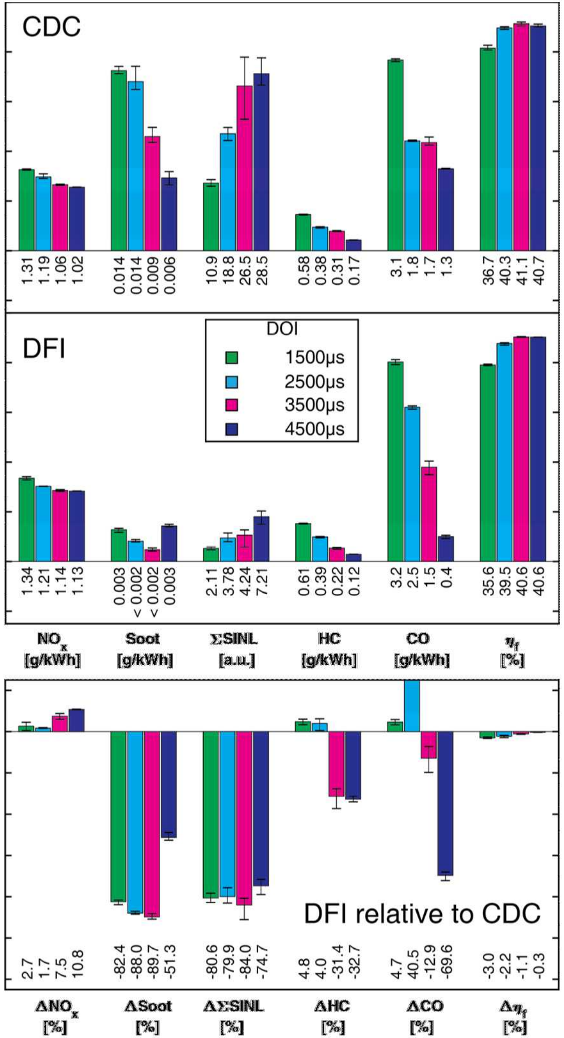
- **DFI attenuates soot significantly**
- **$ISNO_x$ is attenuated with increasing dilution**
  - $ISNO_x$ is higher for DFI than CDC
  - Maybe due to earlier CA50 for DFI
- **Efficiency is lower for DFI**
  - Except at 12% O_2
- **Soot/NO_x tradeoff with dilution is broken**
- **Benefits may continue with more dilution**
- **DFI works better with more dilution**



Duration of injection (DOI) sweep

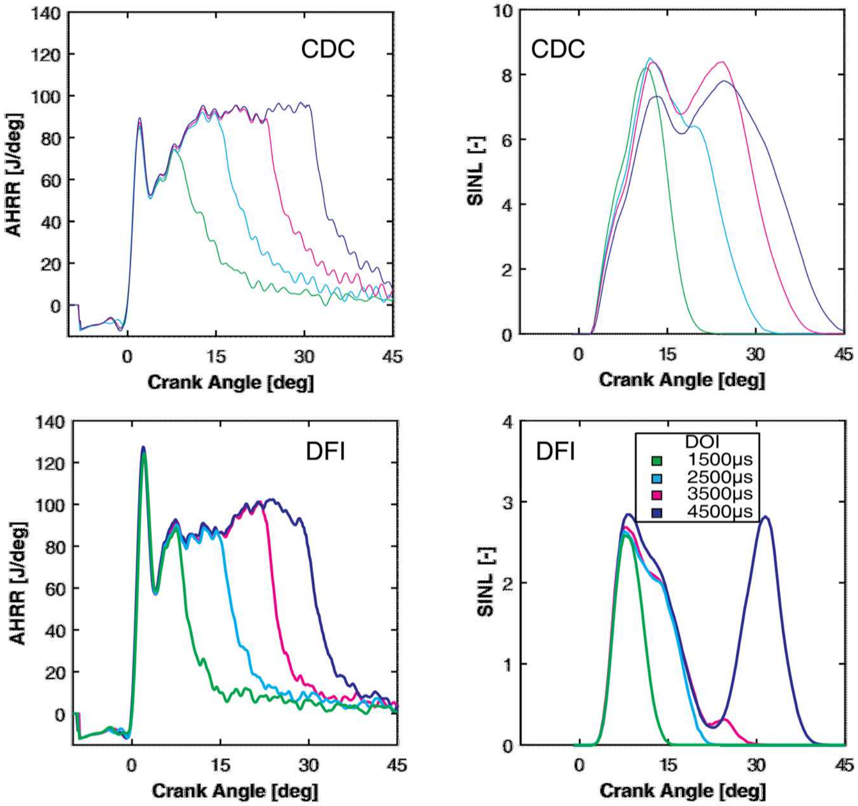
- **Soot is attenuated across the sweep**
  - Up to 90% soot attenuation
- **HC and CO emissions attenuated at longer DOI**
  - Increased at shorter DOIs
- **$ISNO_x$ decreases with increasing DOI**
  - $ISNO_x$ is higher for DFI than CDC
- **Efficiency is lower for DFI than CDC**
  - Difference in efficiency decreases at longer DOI
- **DFI works better with longer DOI**

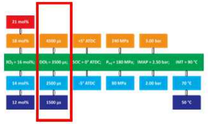




DOI sweep (ISSoot flare-up)

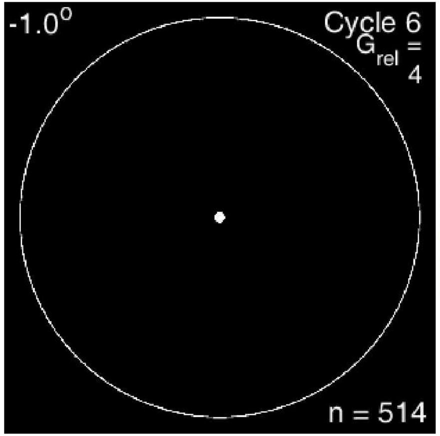
- **ISSoot increases for DFI when DOI > 3500 μs**
- **DFI has a secondary peak in the SINL curve**
  - This starts at ~23 CAD
- **Secondary peak reaches same value as first peak for 4500 μs DOI**
- **Same behavior not observed with CDC**
- **Does not impact AHRR**

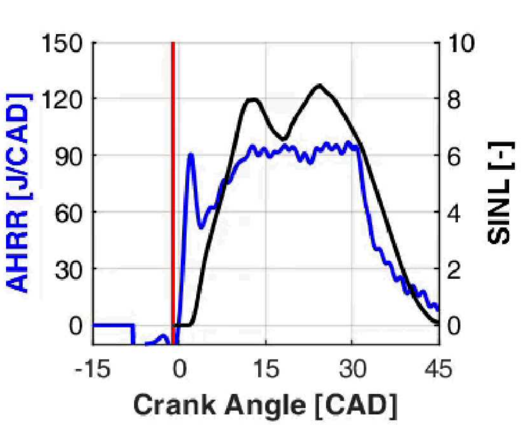




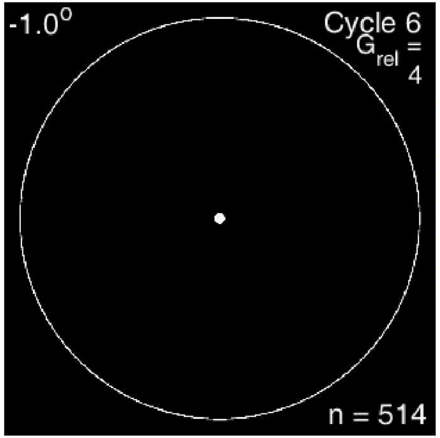
Duration of injection sweep (NL movies 4500μs)

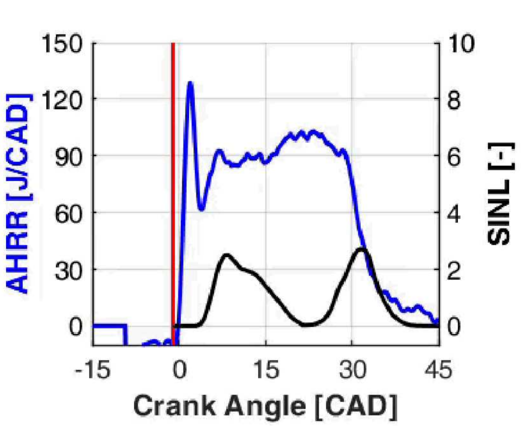
CDC

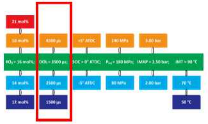




DFI

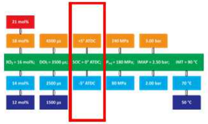


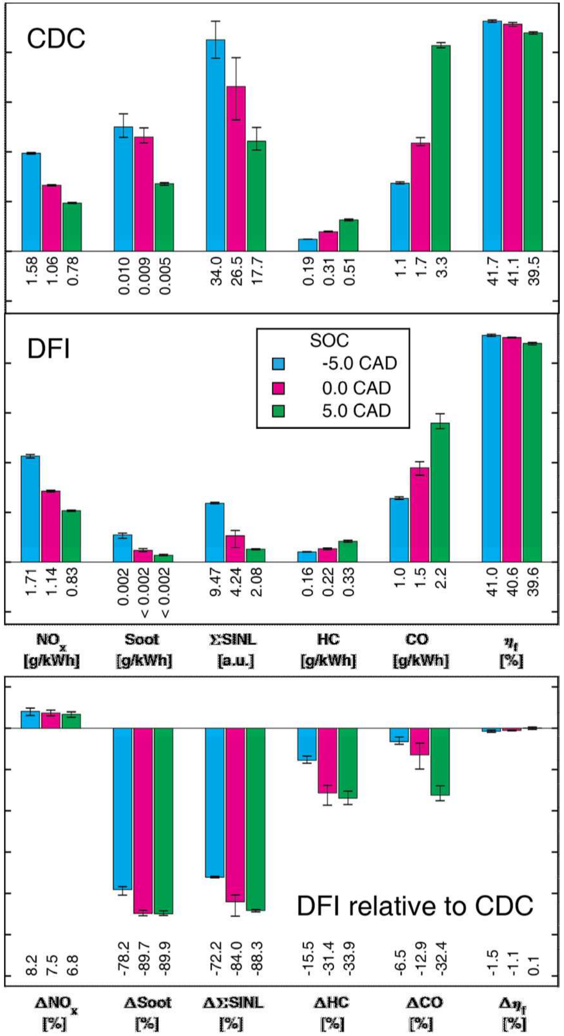




Start of combustion (SOC) sweep

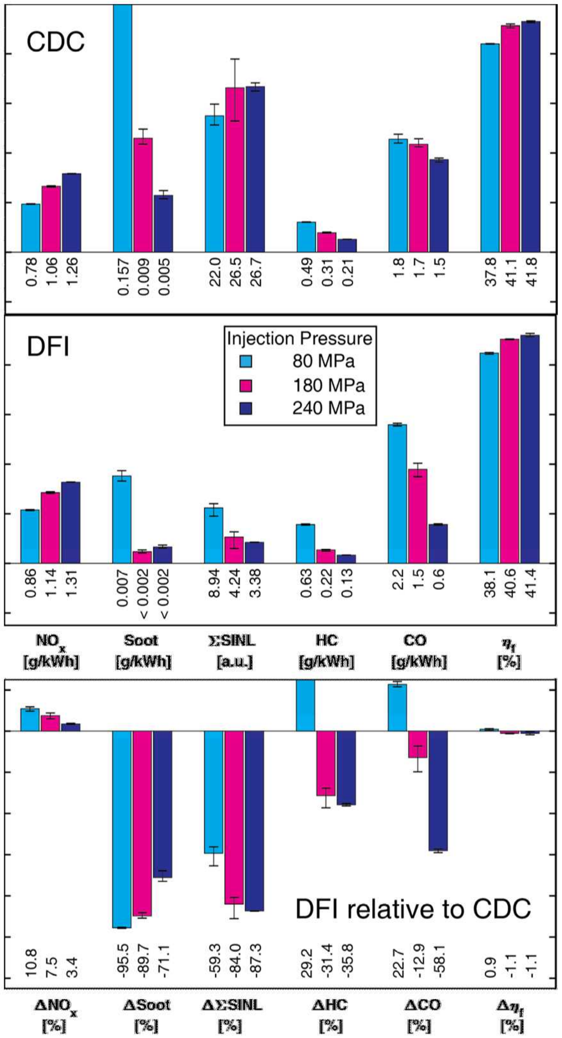
- **Soot emissions (ISSoot) are attenuated**
  - ISSoot is attenuated by between 78% and 90%
  - SINL is reduced by similar amounts
- **$ISNO_x$ increases with DFI**
  - $ISNO_x$ increases by 7 to 8% for DFI
- **Efficiency is lower for DFI**
  - Except at 5.0 CAD
- **DFI responds to SOI shift similarly to CDC**





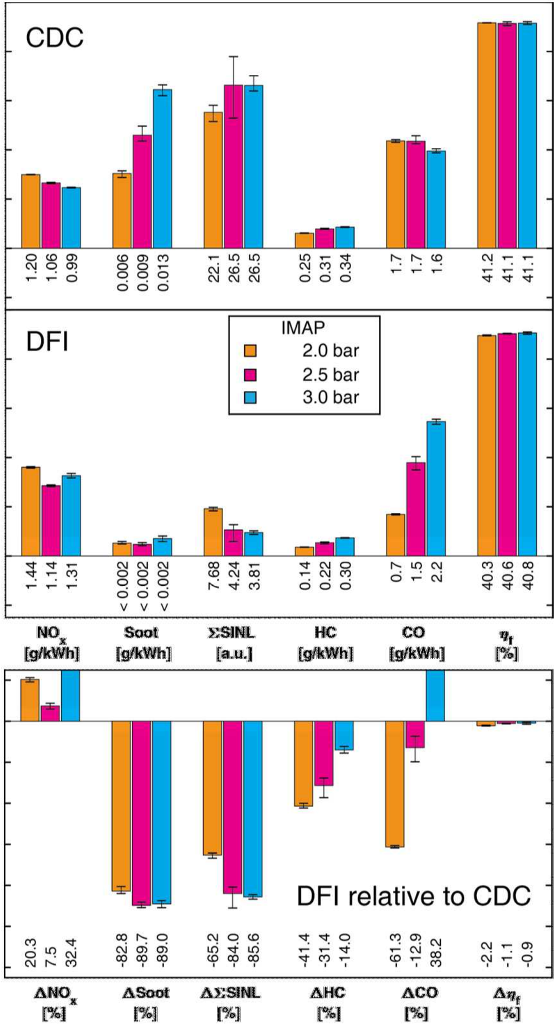
Injection pressure sweep

- **Soot emissions are attenuated**
  - ISSoot is attenuated by up to 96% at 80 MPa
  - ΣSINL is attenuated by 59% at this point
- **$ISNO_x$ increases with DFI**
  - $ISNO_x$ increases by between 3% and 11% for DFI
- **HC and CO emissions attenuated at 180 and 240 MPa**
- **DFI efficiency increases at 80 Mpa**
- **DFI performs better with higher injection pressures**



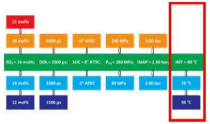
Intake manifold abs. pressure (IMAP) sweep

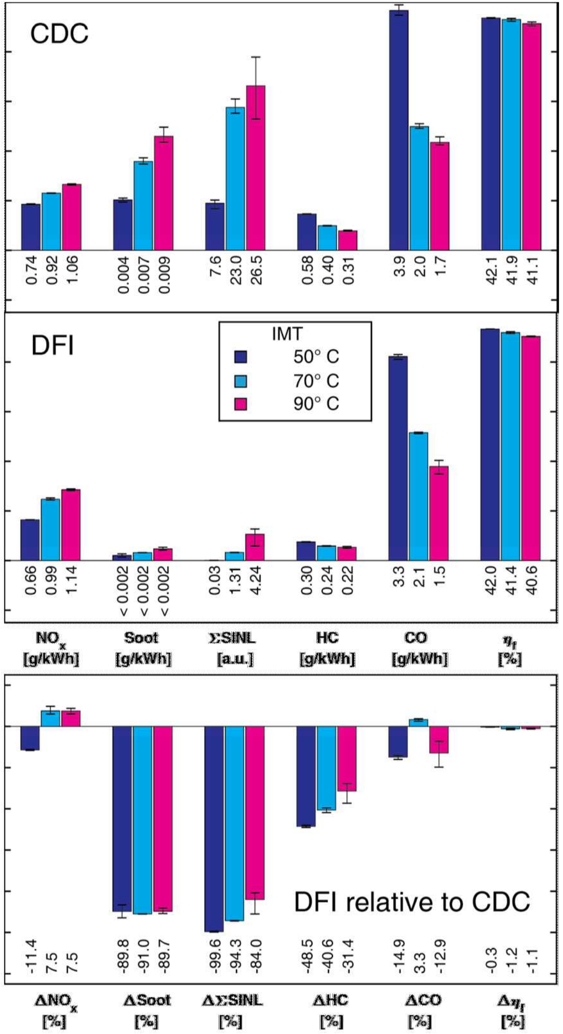
- **Soot emissions are attenuated**
  - ISSoot is attenuated by between 83% and 89%
- **ISNO$_x$ increases with DFI**
  - ISNO$_x$ decreases from 2.0 to 2.5 bar for CDC and DFI
  - From 2.5 to 3.0 bar CDC ISNO$_x$ decreases and DFI ISNO$_x$ increases
- **HC emissions are attenuated by DFI**
- **CO emissions**
  - Increase with IMAP for DFI
  - Decrease slightly with IMAP for CDC
- **DFI works better at lower IMAP**



Intake manifold temperature (IMT) sweep

- **Soot emissions (ISSoot) are attenuated**
  - ISSoot is attenuated by ~90% at all temperatures
  - 99.6% reduction in ΣSINL at 50 °C
- **$ISNO_x$ increases with DFI**
  - $ISNO_x$ increases by 7.5% for DFI at 70 °C and 90 °C
  - $ISNO_x$ is attenuated by 11 % by DFI at 50 °C
- **DFI attenuates HC at all points**
- **Efficiency is slightly decreased by DFI**
- **DFI works better at lower IMT**



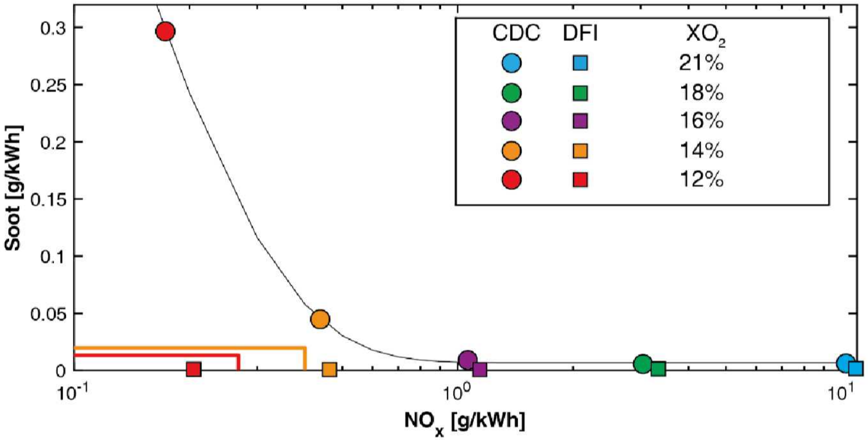


Conclusion

- **DFI attenuates engine-out soot at all the conditions in this study and can attenuate soot by well over an order of magnitude for certain conditions**

- **DFI has been observed to break the soot/NO_x tradeoff**
  - Its performance is improved by increasing dilution!

- **DFI can be used effectively with a 4-orifice injector tip, allowing for increased load over that reached in previous studies**



Future work

- **DFI**
  - Duct geometry effects
    - Test different duct lengths and d
  - Study the effect of oxygenates wi
    - Molecular structure
    - Ignition quality
    - Oxygen content
  - Test over a wider load range
- **Diesel surrogate fuels**
  - Complete study of CRC Project A\
    surrogates
- **Vertical laser-induced incandesce**
  - Unfunded collaboration with Mat