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Characterization of the Effects of Ducted Fuel Injection in a Compression Ignition Engine

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Christopher Nilsen's Exit Seminar

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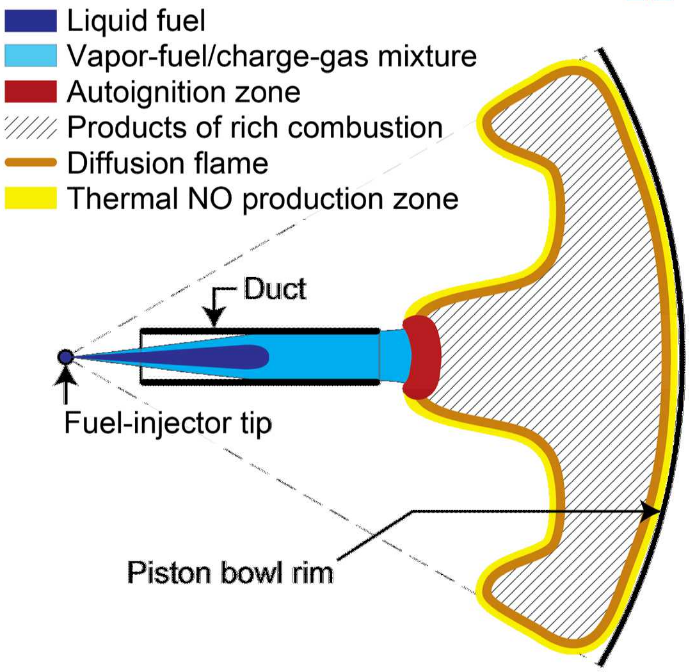
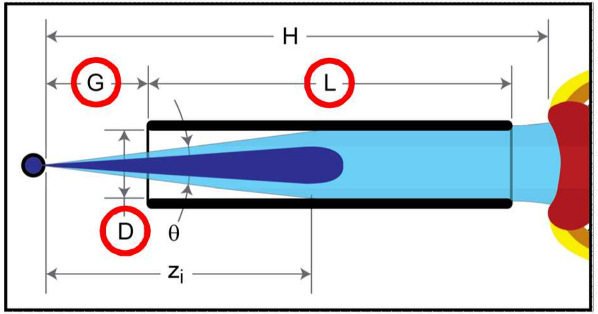
What Is Ducted Fuel Injection (DFI)?

- **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 and other emissions
  - to lower engine system cost and improve performa
- **Key DFI parameters**

  D2L16G3.8δ

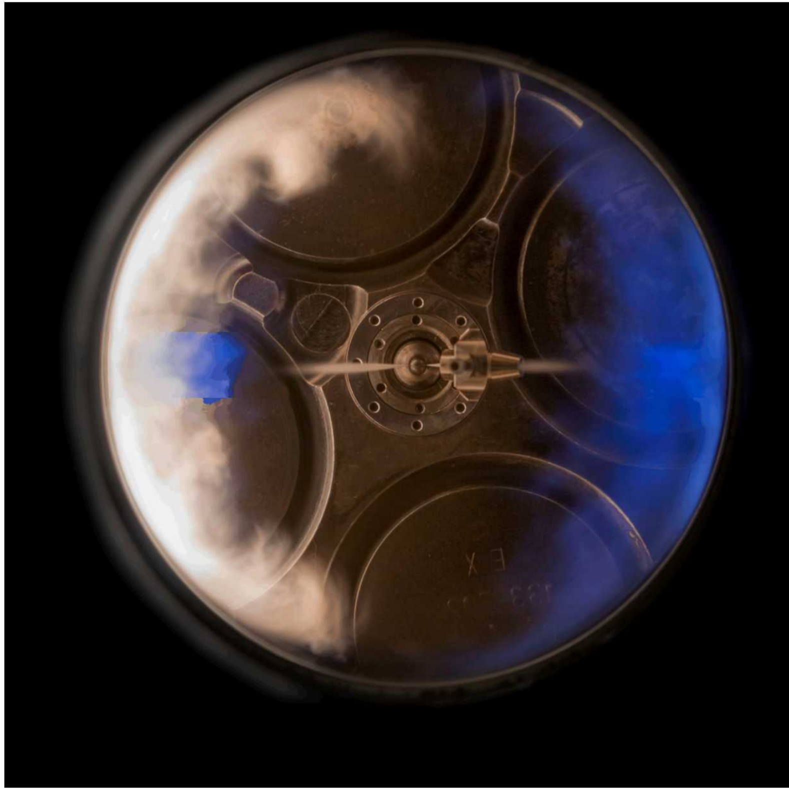
  - Inner diameter (D [mm])
  - Length (L [mm])
  - Standoff distance (G [mm])
  - Inlet/outlet shape (Greek letter)





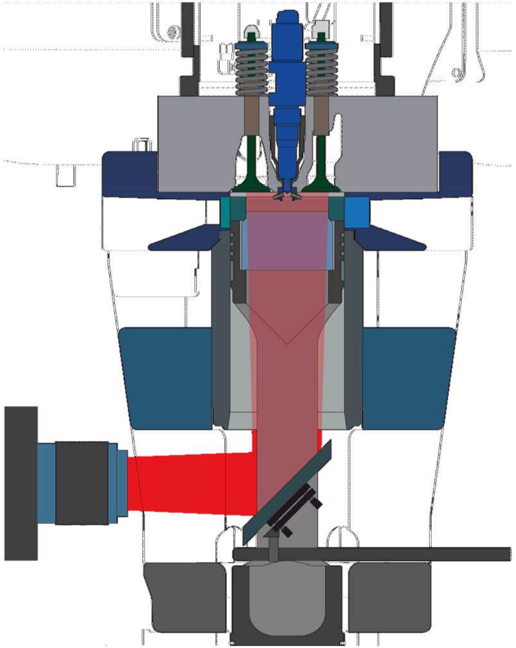
Why does DFI matter?

- **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



Aims

- Quantify the efficiency and engine out emissions of a DFI equipped engine vs a conventional diesel engine under the same load with and without EGR using two ducts. Use a numerical model to develop an understanding of some of the effects of DFI.



- Quantify the effec ne out emissions
  relative to the bas ngine input
  parameters includ l injection pressure,
  load, and percent an understanding of
  the actual effects n the engine.

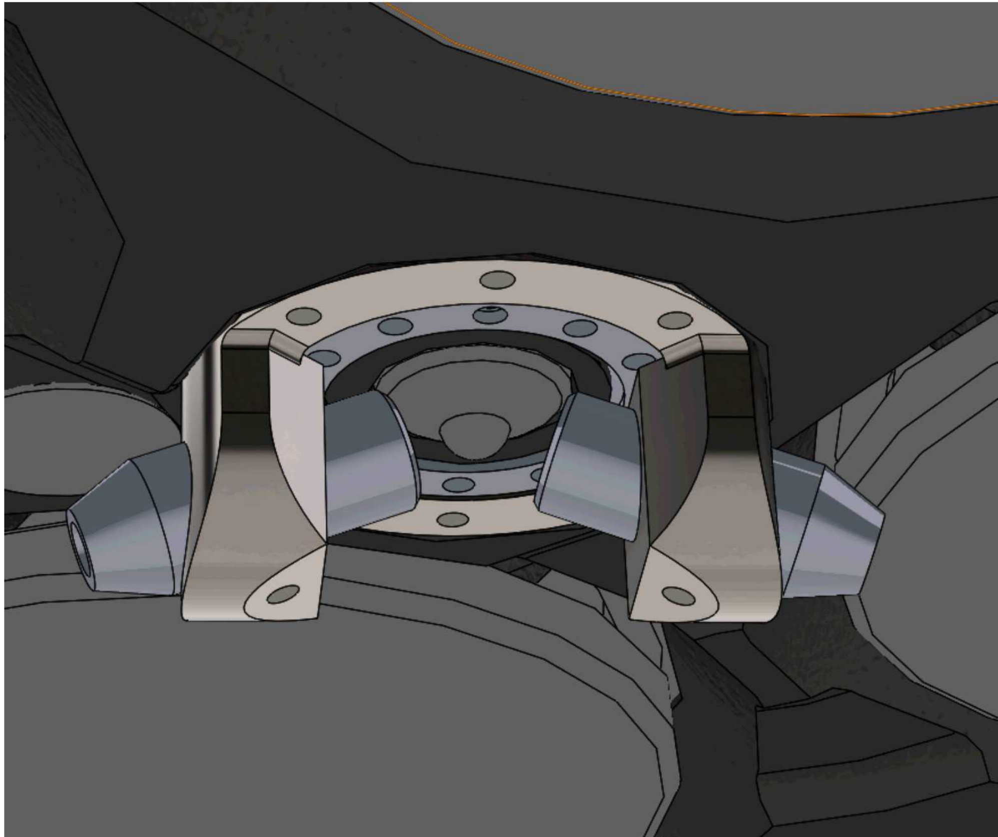
- Show the feasibilit s. This will be done
  by achieving high ve effect of DFI.

Aim 1

Proof of Concept

Overview of “Engine DFI” proof of concept experiments

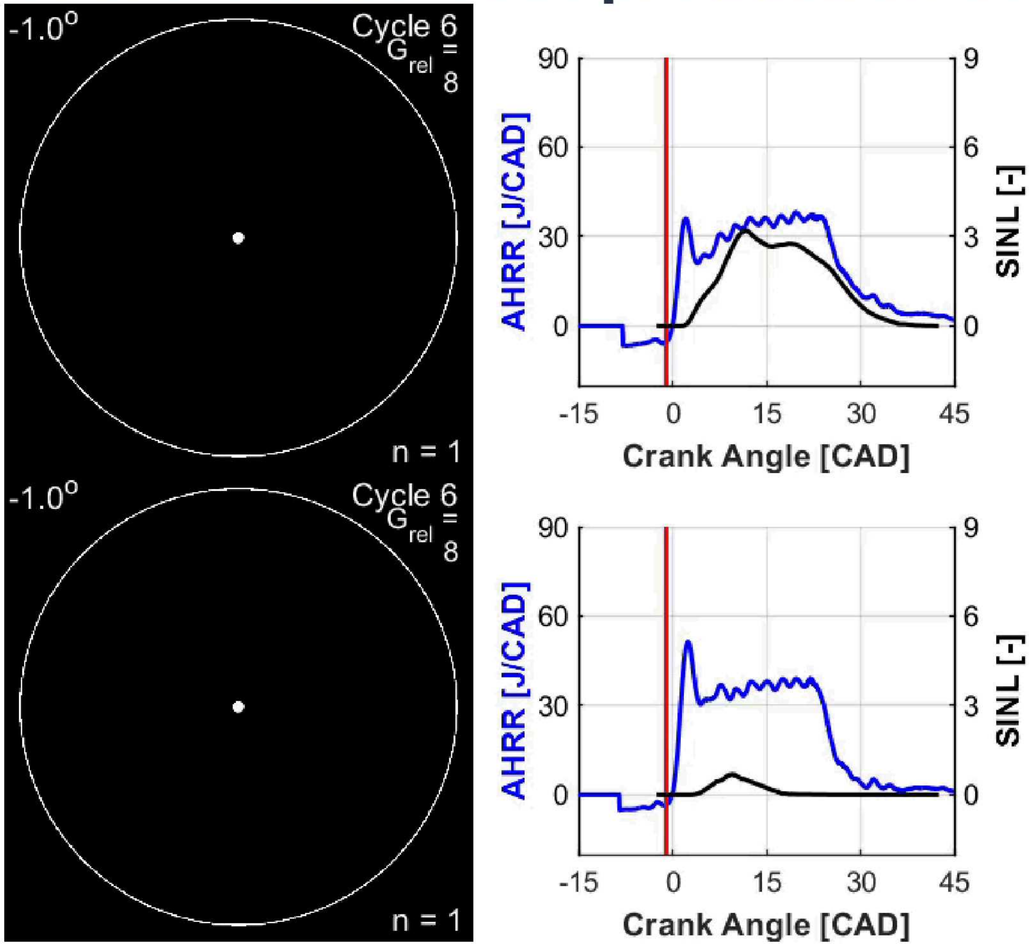
- **Test matrix**
  - D2L12G1.6δ duct tested vs. free spray at 16 mol% O_2 and 21 mol% O_2
- **Stainless-steel duct**
- **No. 2 S15 diesel cert. fuel (CFA)**
  - ~30 wt% aromatics
- **Start of combustion (SOC) = TDC**
- **P_{int} = 2.00 bar, T_{int} = 90 °C**
- **110 µm orifice diameter, 2 hole tip,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



DFI curtails or eliminates soot production at 16% O_2

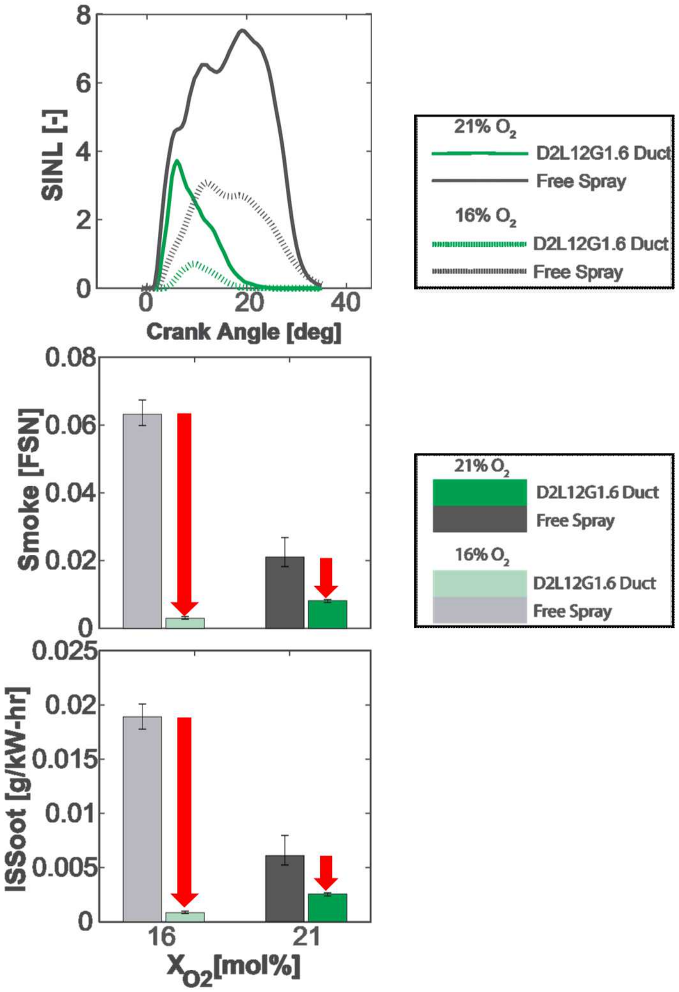
Free Spray

DFI



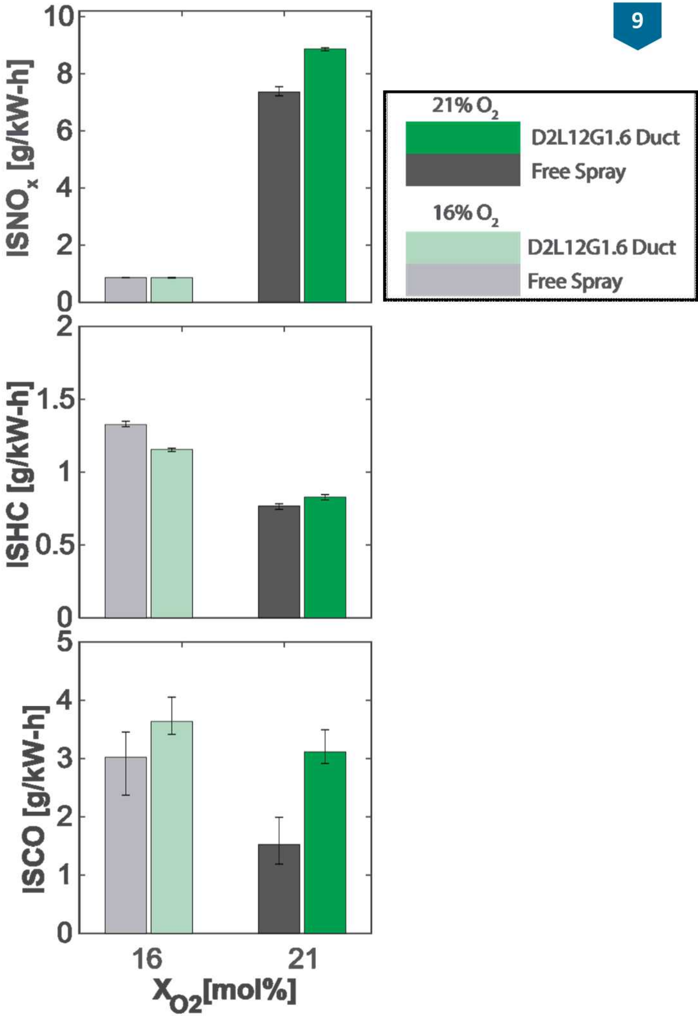
DFI consistently attenuates soot!

- **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



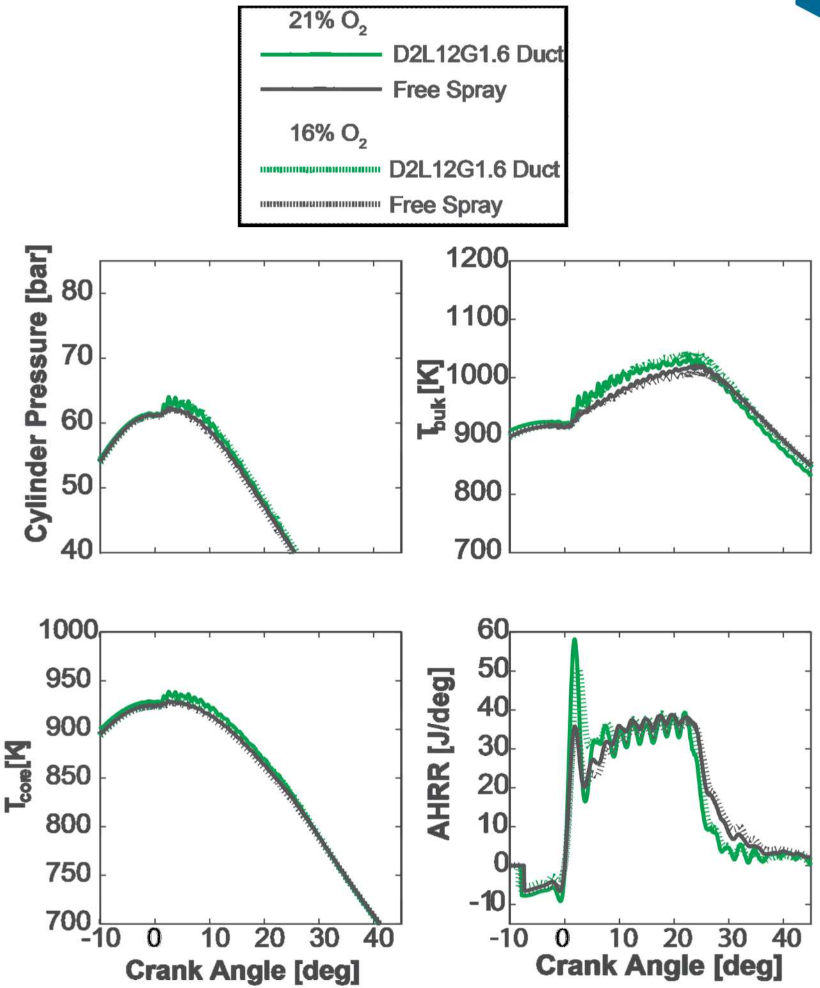
What effect does DFI have on other engine-out emissions?

- 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



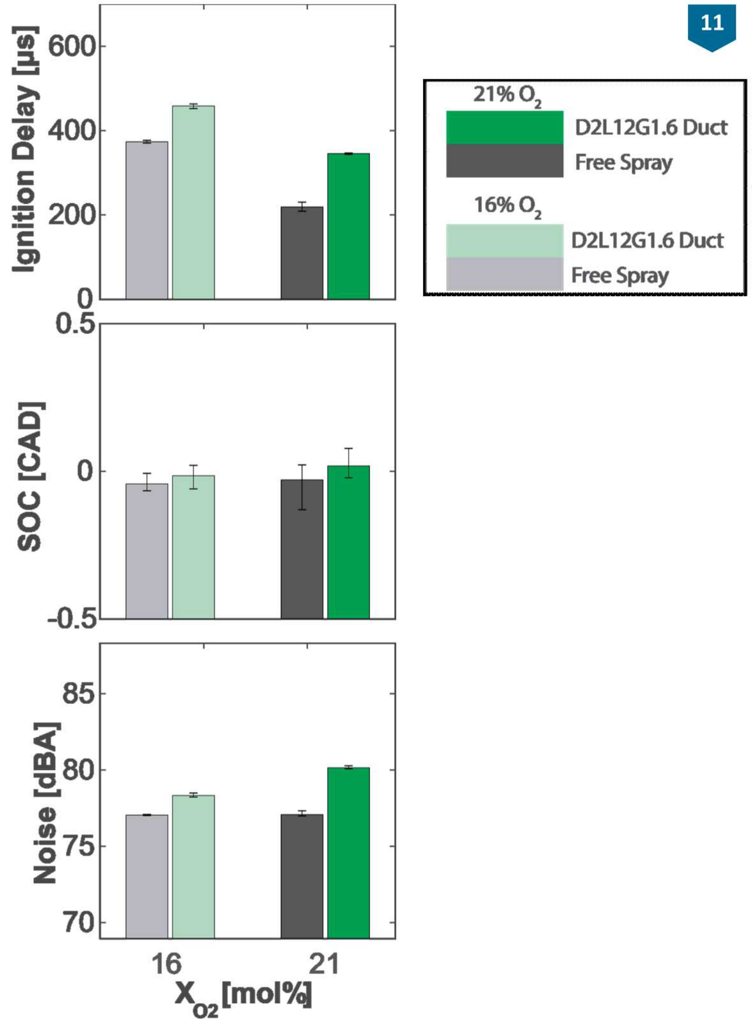
Effects of DFI on pressure, temperature, and AHHR

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



DFI stability and controllability

- Ignition delay is longer for DFI at both 16% O_2 and 21% O_2
- The ignition delay for each case is stable
- SOC occurred consistently at TDC
- DFI responded to SOI changes similarly to conventional diesel combustion
- The combustion noise for DFI is higher
  - 3 dB higher at 21% O_2
  - 1 dB higher at 16% O_2



Summary

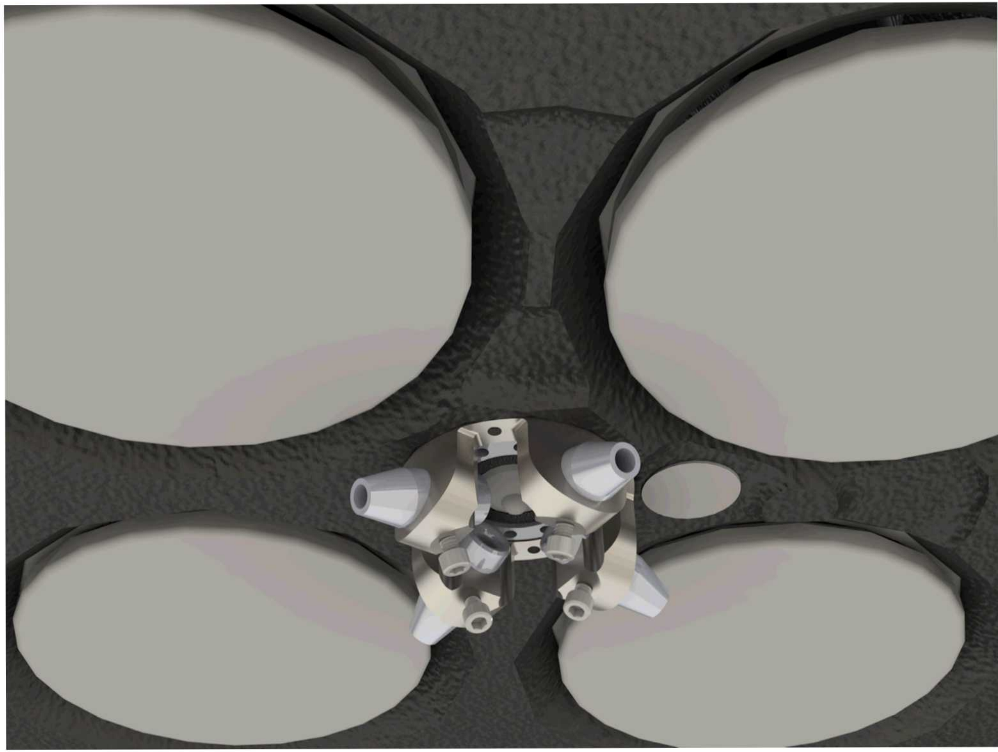
- **DFI attenuates engine-out soot emissions in our mixing-controlled compression-ignition engine**
- **DFI relative to free spray under the same conditions**
  - Ignition delay is longer
  - Combustion duration is shorter and late-cycle burn-out is faster
    - This is particularly true at 16% O_2
  - DFI improves some engine-out emissions
- **DFI emissions performance is improved by increasing dilution to 16% O_2**
  - We don't yet know where this beneficial effect ends

Aim 2 Experiments

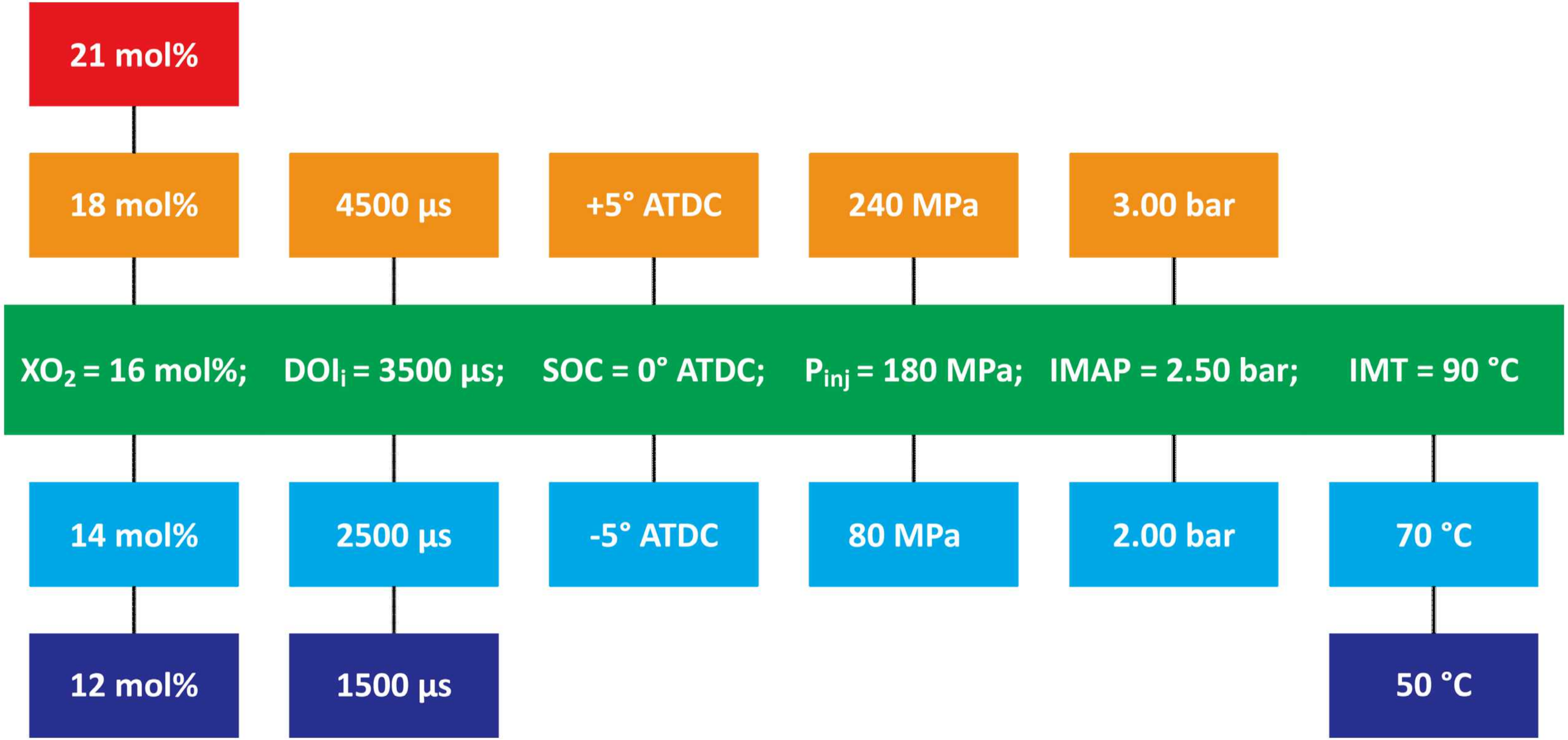
Develop understand of how DFI works

Overview of “Engine DFI” parameter sweep experimental baseline

Experimental Conditions	
Fuel	No. 2 S15 diesel cert. fuel CFB
Speed	1200 rpm
Duration of injection	3500 µs
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	2.5 bar
Intake manifold temperature	90 °C
Coolant temperature	90 °C



“Engine DFI” parameter sweep



IMAP correction

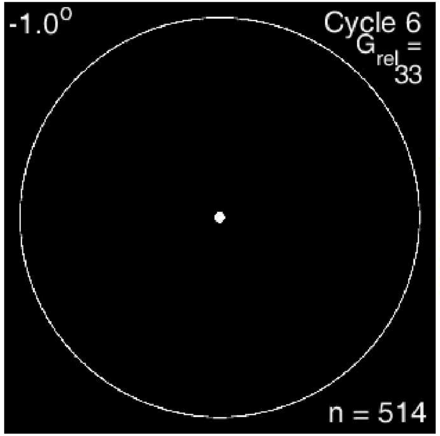
- **The optical engine has a 12.5:1 compression ratio compared to 16.5:1 in a typical modern diesel**
- **Match TDC conditions assuming isentropic compression**

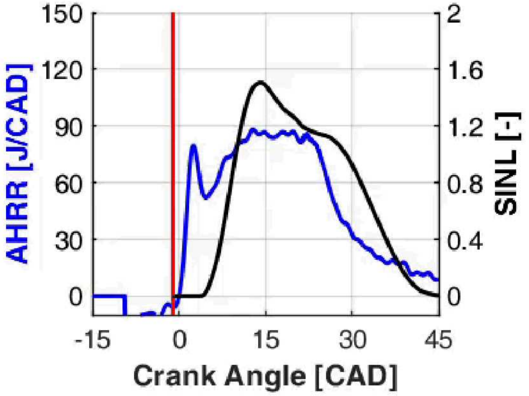
$$\frac{p_1}{p_2} = \left(\frac{V_2}{V_1}\right)^k = \left(\frac{T_1}{T_2}\right)^{\frac{k}{k-1}}$$

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

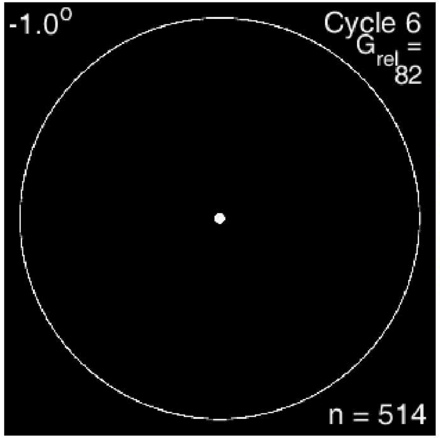
Dilution sweep (NL movies 12 mol% O_2)

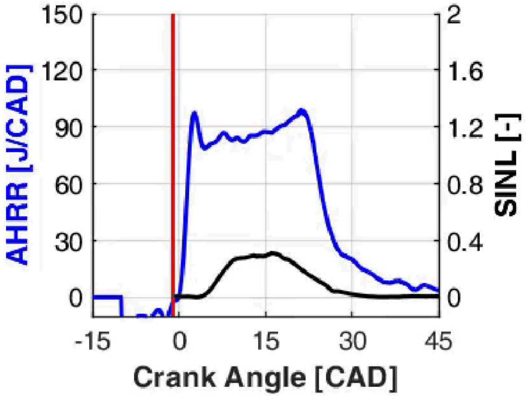
CDC





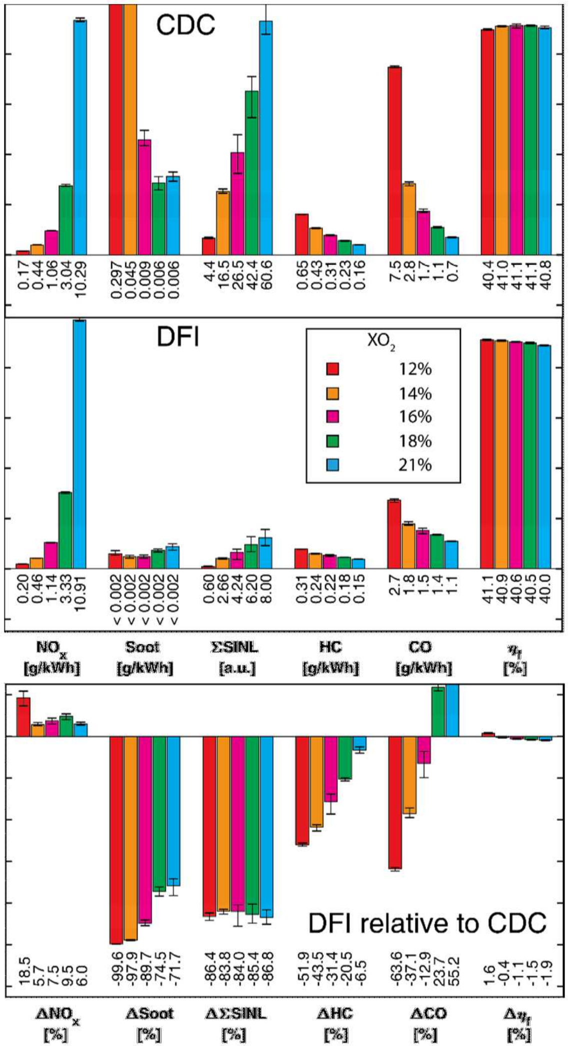
DFI





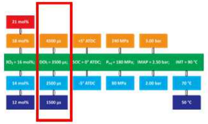
Dilution sweep

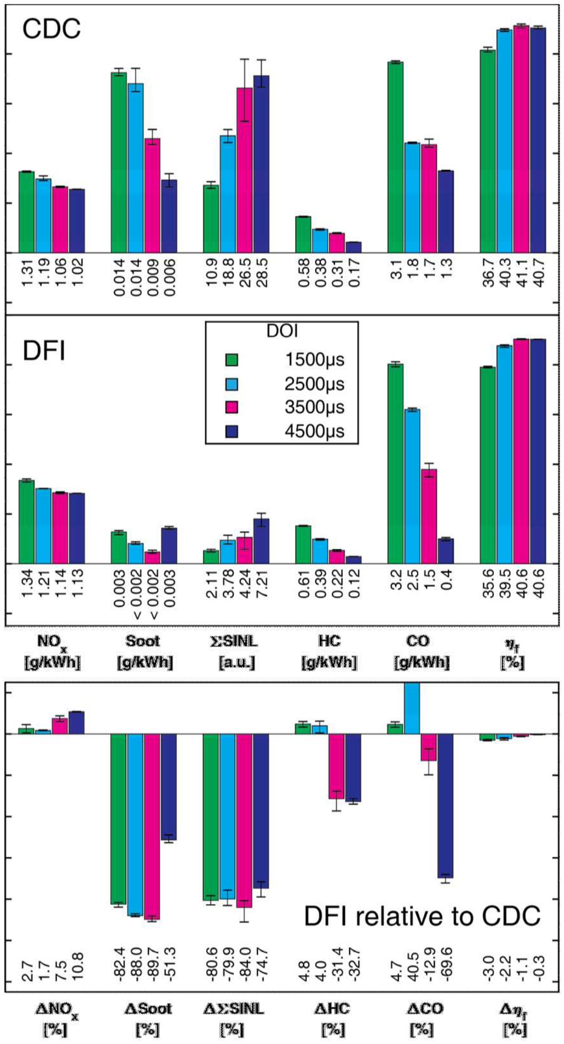
- **DFI attenuates soot significantly**
- **$ISNO_x$ is attenuated with increasing dilution**
  - $ISNO_x$ is higher for DFI than CDC
  - Maybe due to earlier CA50 for DFI
- **Efficiency is lower for DFI**
  - Except at 12% O_2
- **Soot/NO_x tradeoff with dilution is broken**
- **Benefits may continue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



Duration of injection (DOI) sweep

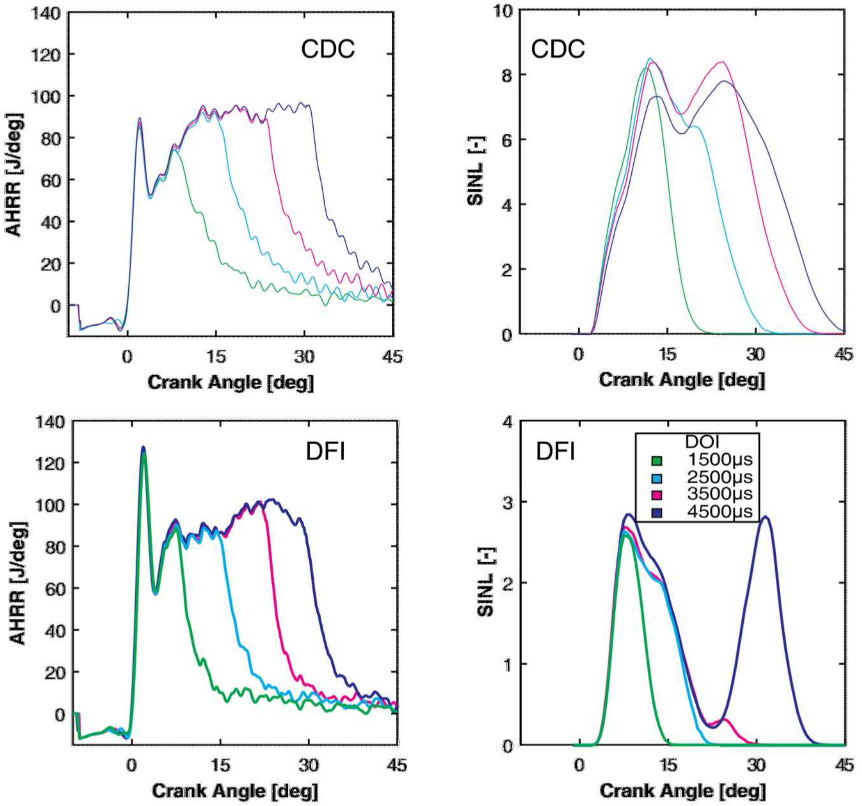
- **Soot is attenuated across the sweep**
  - Up to 90% soot attenuation
- **HC and CO emissions attenuated at longer DOI**
  - Increased at shorter DOIs
- **$ISNO_x$ decreases with increasing DOI**
  - $ISNO_x$ is higher for DFI than CDC
- **Efficiency is lower for DFI than CDC**
  - Difference in efficiency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

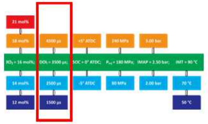




DOI sweep (ISSoot flare-up)

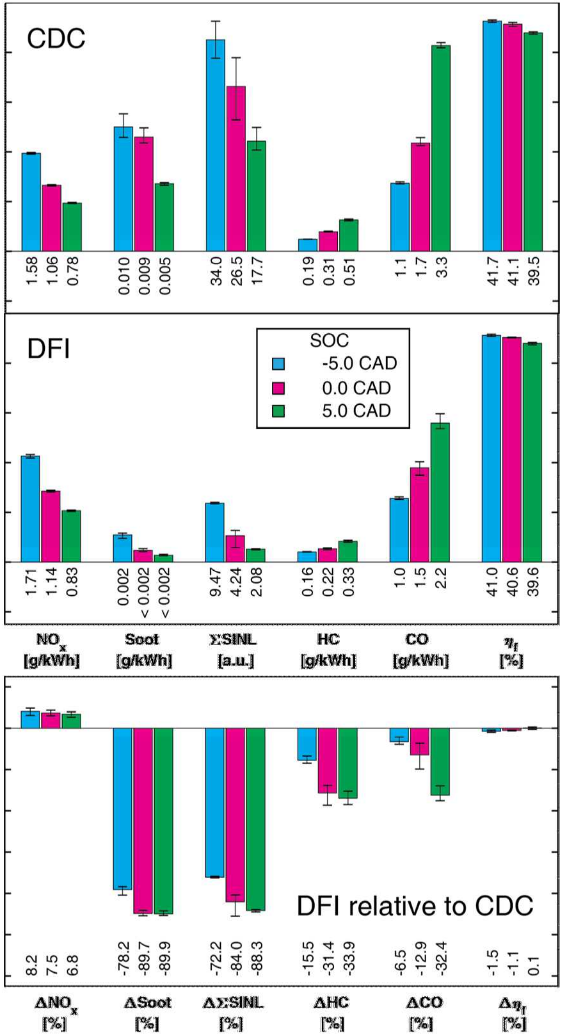
- **ISSoot increases for DFI when DOI > 3500 µs**
- **DFI has a secondary peak in the SINL curve**
  - This starts at ~23 CAD
- **Secondary peak reaches same value as first peak for 4500 µs DOI**
- **Same behavior not observed with CDC**
- **Does not significantly impact AHRR**

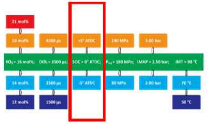




Start of combustion (SOC) sweep

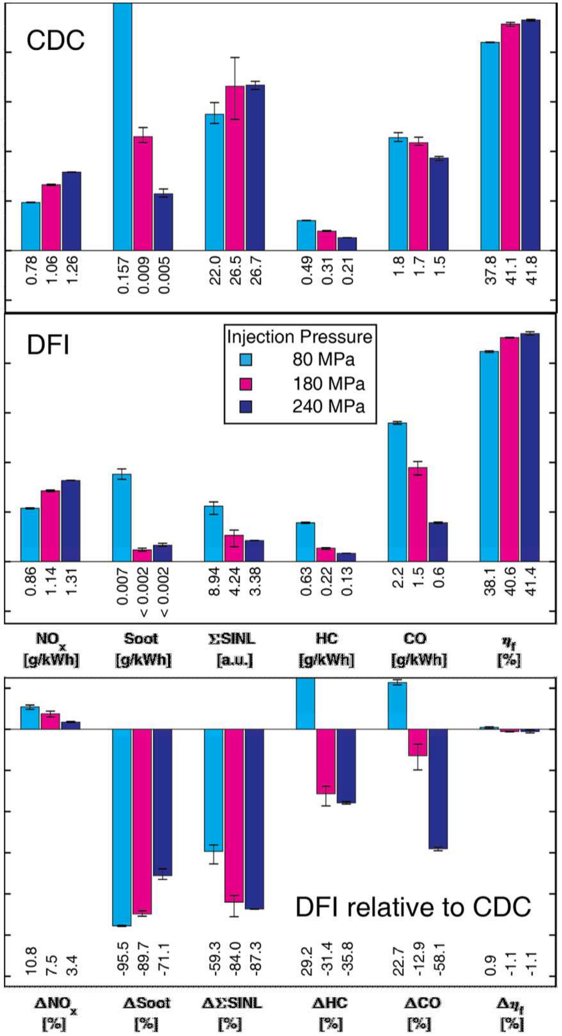
- **Soot emissions (ISSoot) are attenuated**
  - ISSoot is attenuated by between 78% and 90%
  - SINL is reduced by similar amounts
- **$ISNO_x$ increases with DFI**
  - $ISNO_x$ increases by 7 to 8% for DFI
- **Efficiency is lower for DFI**
  - Except at 5.0 CAD
- **DFI responds to SOC shift similarly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





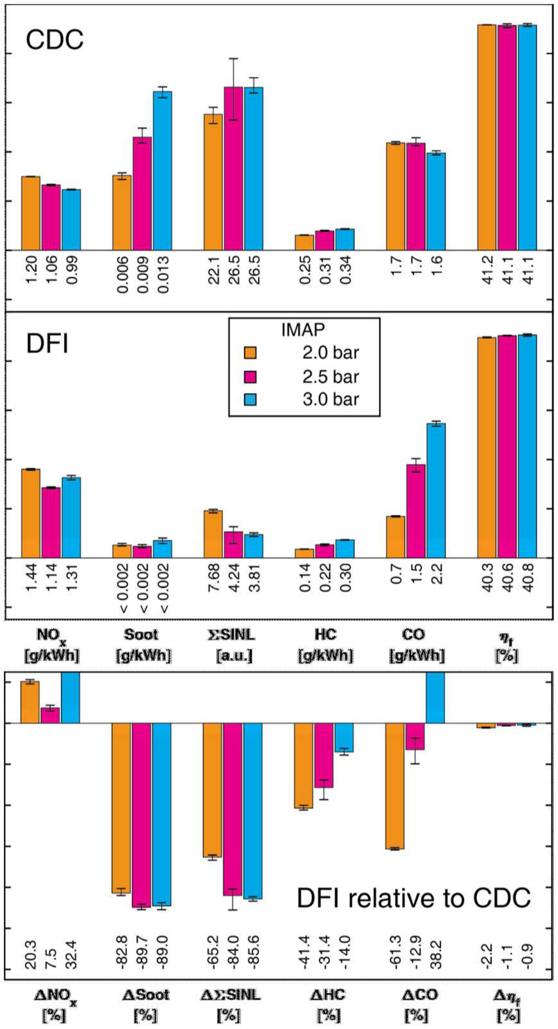
Injection pressure sweep

- **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 generally performs better with higher injection pressures**



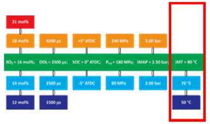
Intake manifold abs. pressure (IMAP) sweep

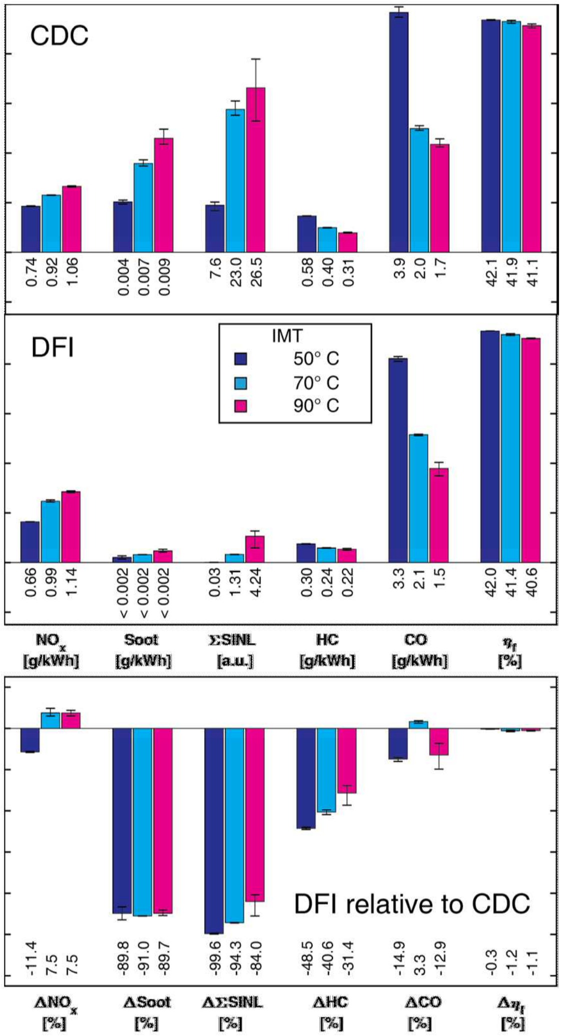
- **Soot emissions are attenuated**
  - ISSoot is attenuated by between 83% and 89%
- **$ISNO_x$ increases with DFI**
  - $ISNO_x$ decreases from 2.0 to 2.5 bar for CDC and DFI
  - From 2.5 to 3.0 bar CDC $ISNO_x$ decreases and DFI $ISNO_x$ increases
- **HC emissions are attenuated by DFI**
- **CO emissions**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



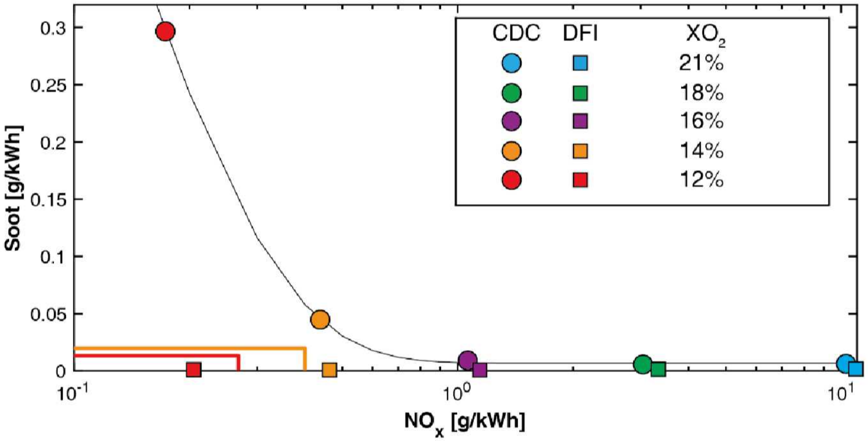


Summary

- **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**
  - 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**

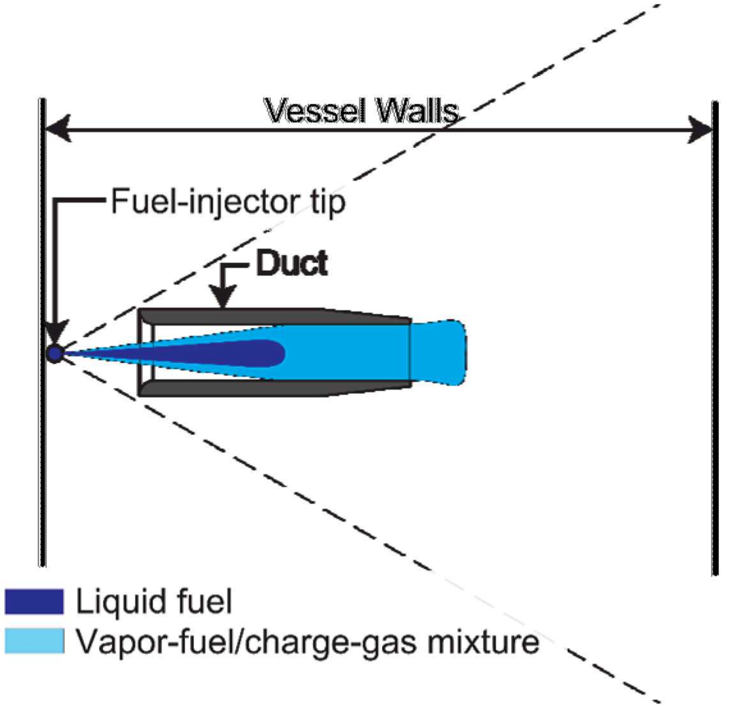


Aim 2 Modeling

Develop understand of how DFI works

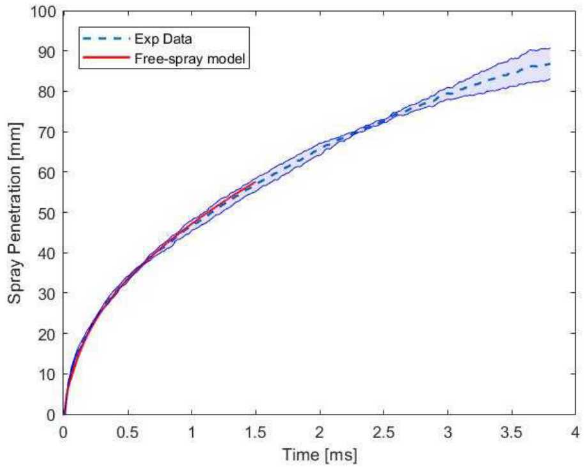
DFI numerical study conditions (Spray A)

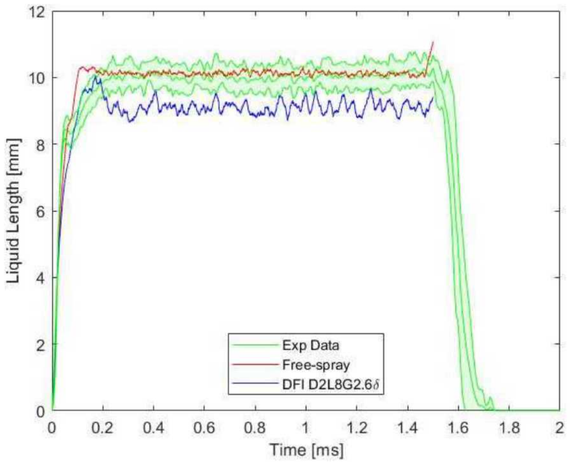
Ambient gas temperature	900 K
Ambient gas pressure	near 6.0 MPa
Fuel injector nominal nozzle outlet diameter	0.090 mm
Number of holes	1 (single hole)
Orifice orientation	Axial
Fuel injection pressure	150 MPa
Fuel	n-dodecane
Fuel temperature at nozzle	363 K (90 °C)
Injection duration	1500 µs
Injection mass	3.5 – 3.7 mg



Free spray validation

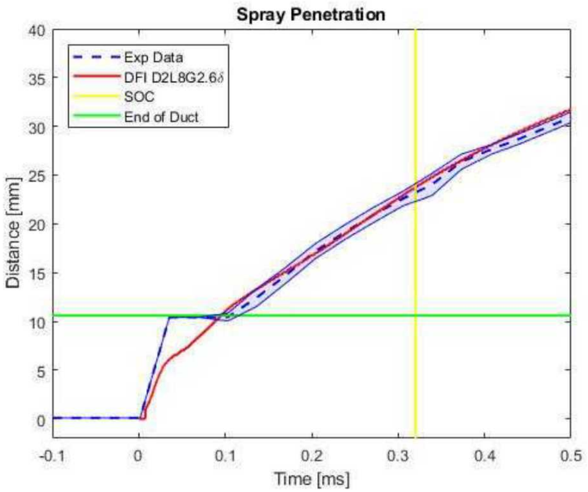
- **Model matches experimental spray penetration**
  - Inside standard deviation for entire duration of injection
- **Model matches liquid lengths well**
  - Steady state value is the same
  - Small difference in initial liquid length
  - DFI model shows slightly shorter liquid length

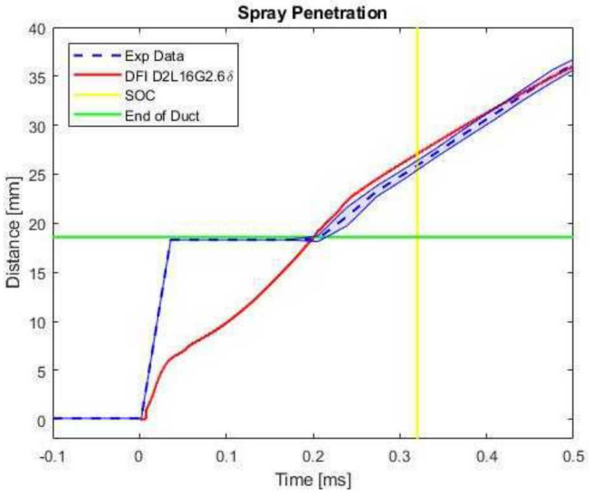




DFI validation (cont.)

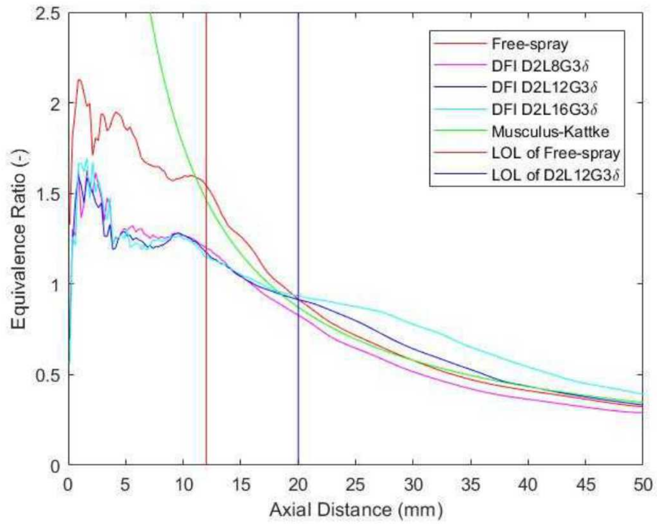
- **DFI spray penetration matches well**
  - Inside standard deviation for entire length of D2L8G2.6δ
  - Good match for D2L16G3δ
- **Step in experimental measurement because spray penetration cannot be measured in duct**

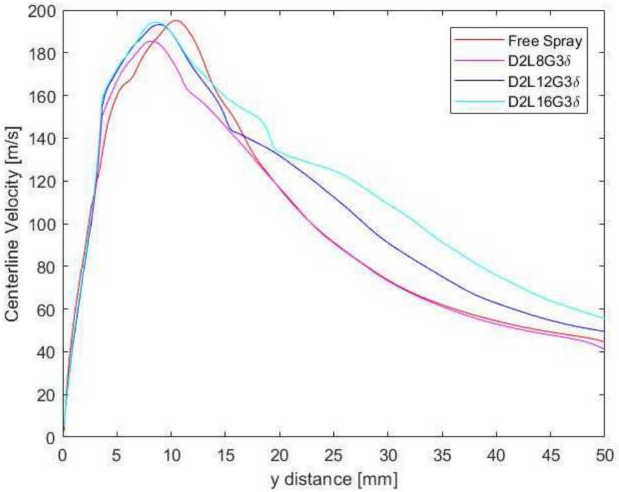




DFI vs free spray

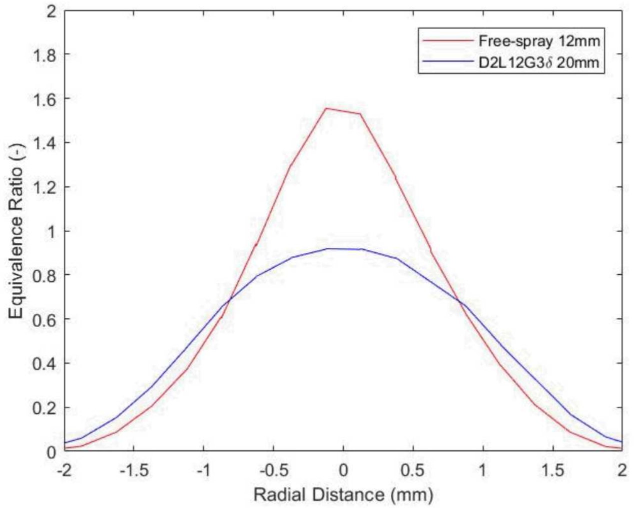
- **Centerline equivalence ratio lower for D2L12G3 up to 20 mm**
  - Liftoff length for DFI ~20mm
  - Liftoff length for free spray ~12mm
- **Centerline velocity higher for D2L12G3 before 10 mm and downstream of the duct**
  - Higher velocities before 10mm may be due to faster spray break up
  - Higher velocities for DFI likely contribute to longer liftoff lengths

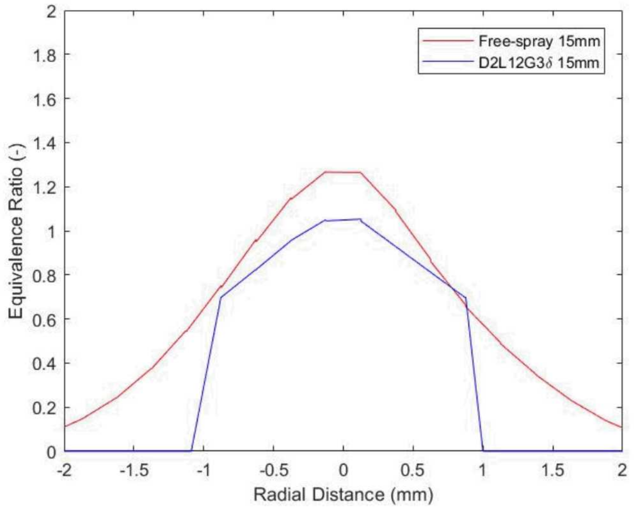




DFI vs free spray (cont.)

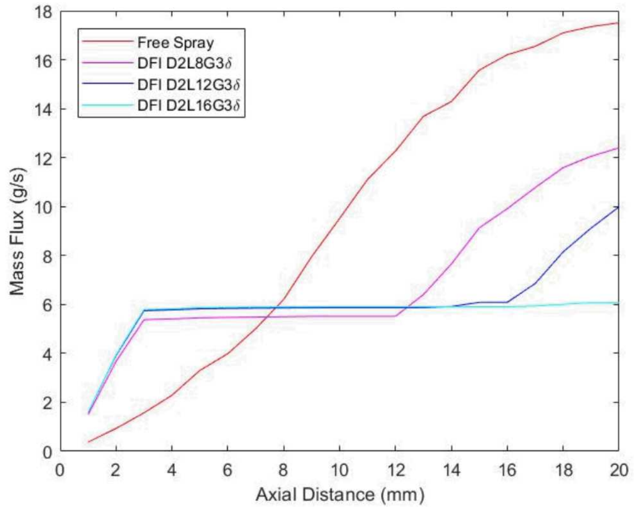
- **DFI has lower equivalence ratio than free spray at LOL**
- **DFI also has lower equivalence ratio at the end of the duct**
- **These seem to show less fuel for DFI**
  - Mass flux of fuel is the same due to higher velocities





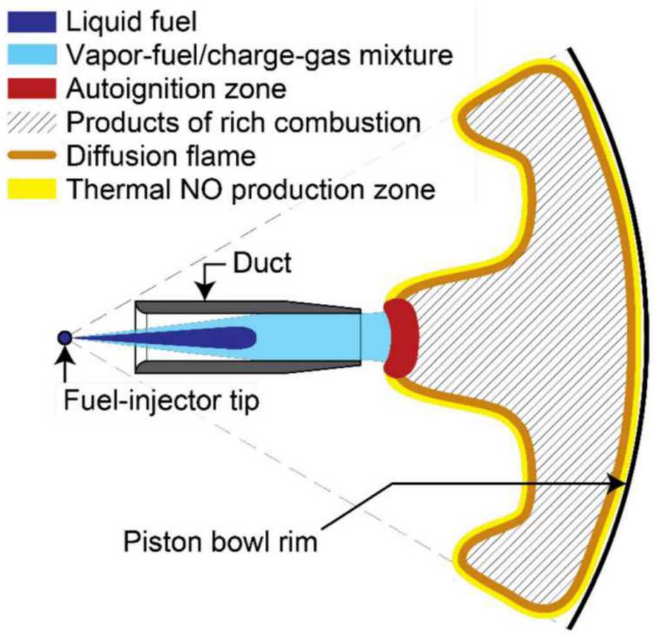
DFI entrainment

- DFI has more entrainment prior to duct entrance
- Free spray had higher entrainment by liftoff length
- Shorter ducts allow for more entrainment
- Suggests effects of DFI are due to enhanced mixing



Summary

- Model of DFI can achieve good match with experimental results
- DFI lowers equivalence ratio at LOL relative to free spray
- DFI allows for both low soot and NO_x levels that are not achievable with CDC at low-load conditions.

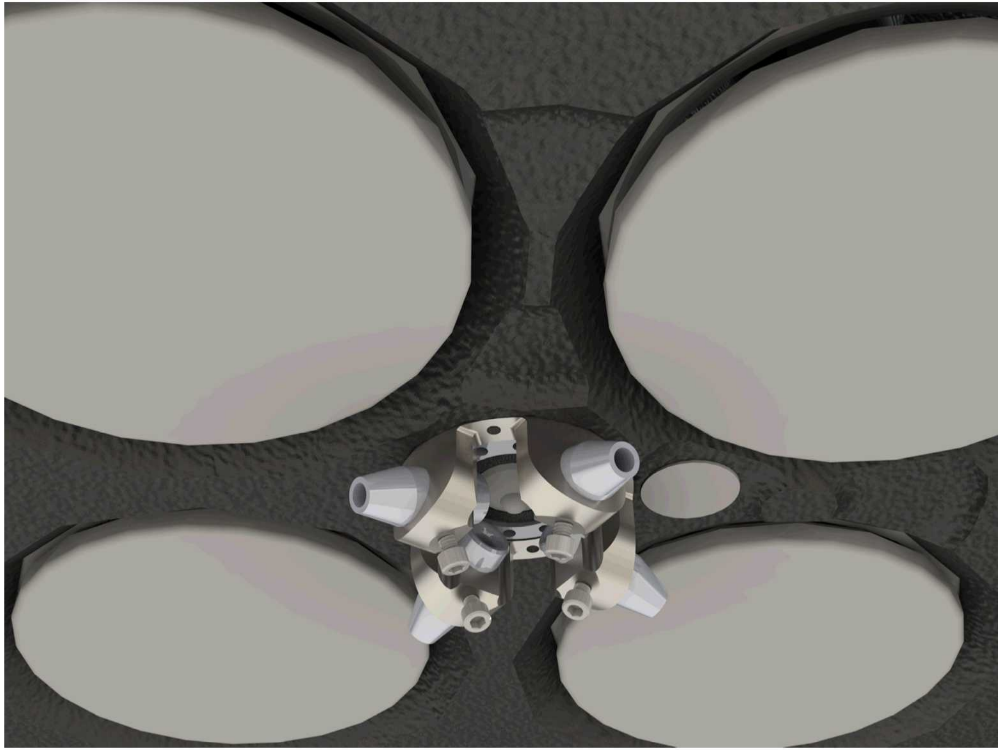


Aim 3

Expand operating parameter space

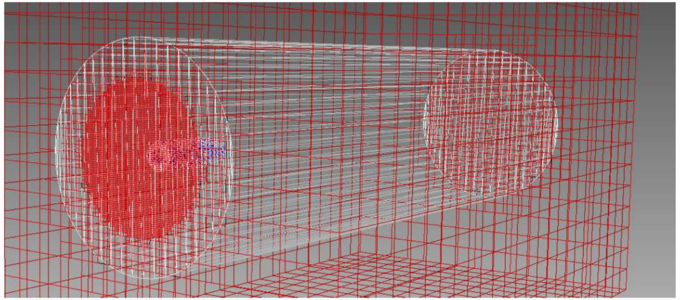
Overview of “Engine DFI” HL and idle parameter sweep experimental baseline

Experimental Conditions		
	Low Load	Higher Load
Fuel	CF_B	
Speed	1200 RPM	
Displacement	1.7 L	
Duration of injection (DOI, commanded)	1250 µs	4500 µs
Injection pressure	80 MPa	240 MPa
Injector-tip configuration	4 × 0.110 mm × 140°	
Ducts	D2L12G3δ vs. none	
Start of combustion timing (SOC)	0.0 CAD ATDC	
Dilution (XO_2)	14, 16, 18 mol% O_2	16 mol% O_2
Intake manifold absolute pressure (IMAP)	1.5 bar	3.0 bar
Intake manifold temperature (IMT)	90 °C	
Coolant temperature	90 °C	



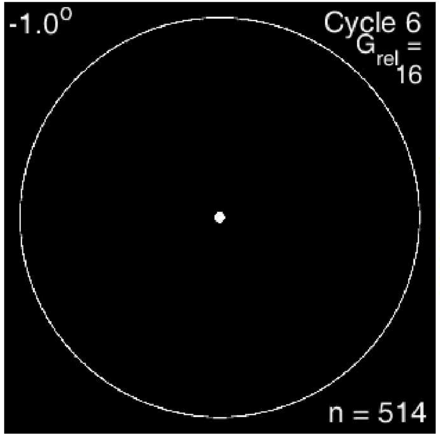
Model set up

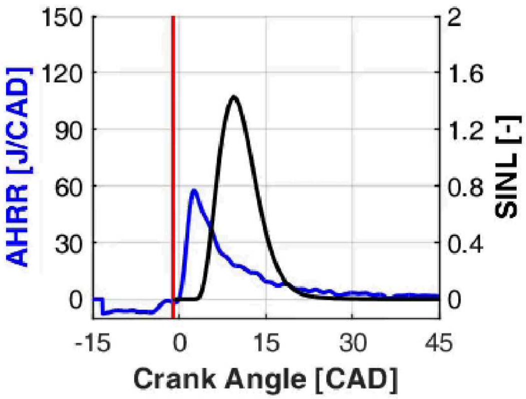
- **Reynolds average Naiver-Stokes (RANS) model use for fluid motion**
  - Low computational cost allowed for multiple runs
- **K-ε turbulence model used to close RANS equations**
- **Liquid fuel modeled as Lagrangian particles**
- **Liquid breakup modeled using Kelvin-Helmholtz Raleigh-Taylor (KHRT)**
  - KH drives primary breakup due to instabilities in liquid jet
  - RT drives secondary breakup due to rapid deceleration



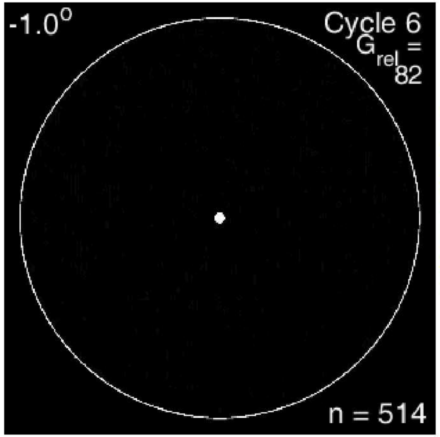
Idle dilution sweep (NL movies 14 mol% O_2)

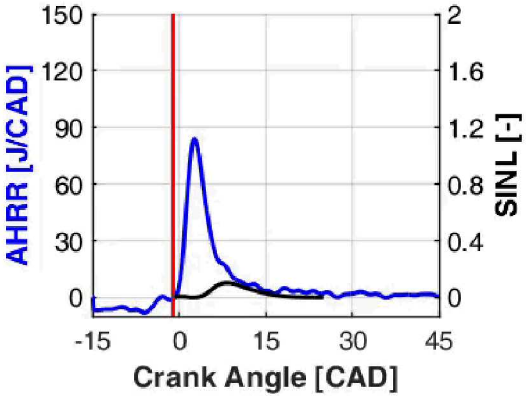
CDC





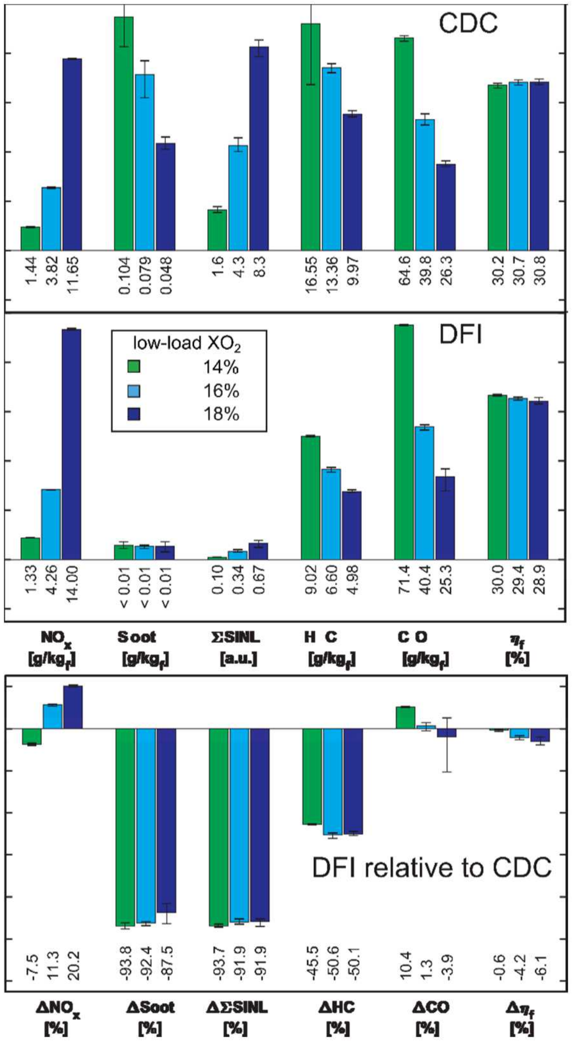
DFI





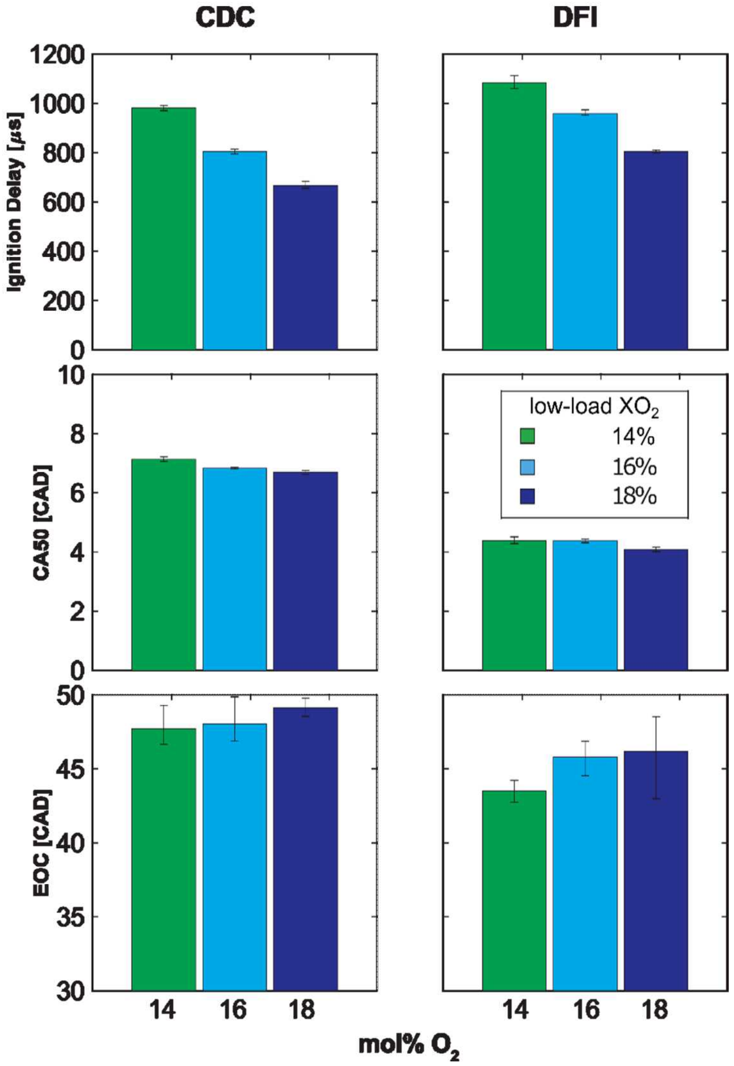
Idle dilution sweep

- **DFI attenuates soot significantly**
- **$ISNO_x$ is attenuated with increasing dilution**
  - $ISNO_x$ is higher for DFI than CDC
  - Except at 14 mol% O_2 where DFI has lower NO_x
- **Efficiency is lower for DFI**
- **Soot/NO_x tradeoff with dilution is broken**
- **Benefits may continue with more dilution**
- **DFI works better with more dilution**



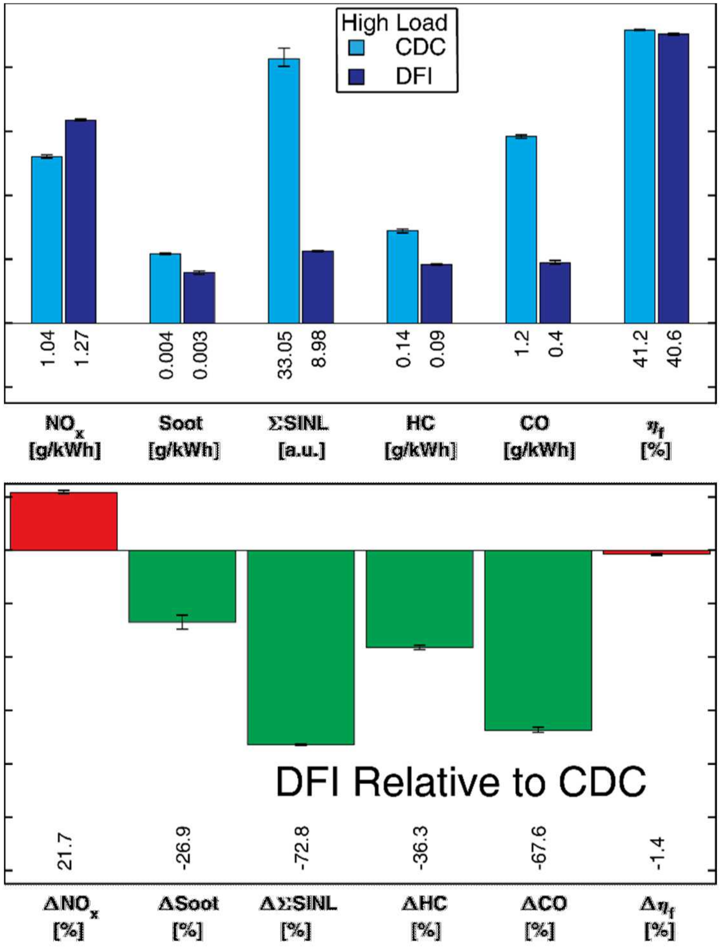
Idle dilution sweep

- **Ignition delay is longer for DFI than CDC**
  - Often observed in DFI testing
- **CA50 is advanced with DFI**
  - This could contribute to the higher NO_x emissions seen with DFI
- **EOC is advanced**
  - Earlier EOC should result in higher efficiency for DFI



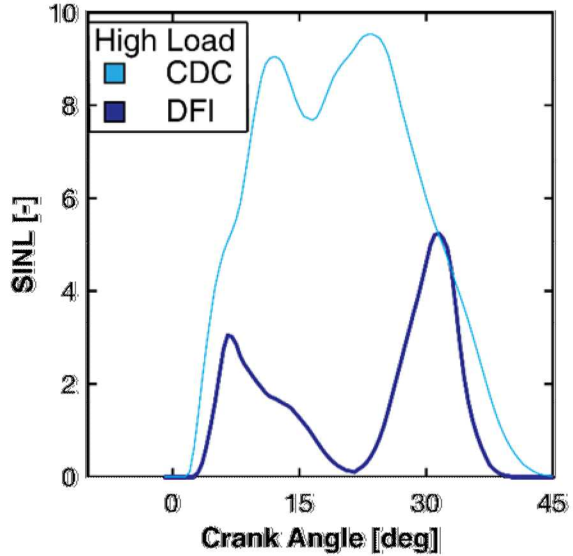
Higher load CDC vs. DFI

- **First study to demonstrate DFI with over 10 bar IMEPg load**
- **Soot is attenuated for DFI**
  - Attenuation of 27%
- **SINL is decreased by more than soot**
  - 73% decrease in ΣSINL
- **HC and CO emission are both attenuated**
- **DFI efficiency is lower than CDC**



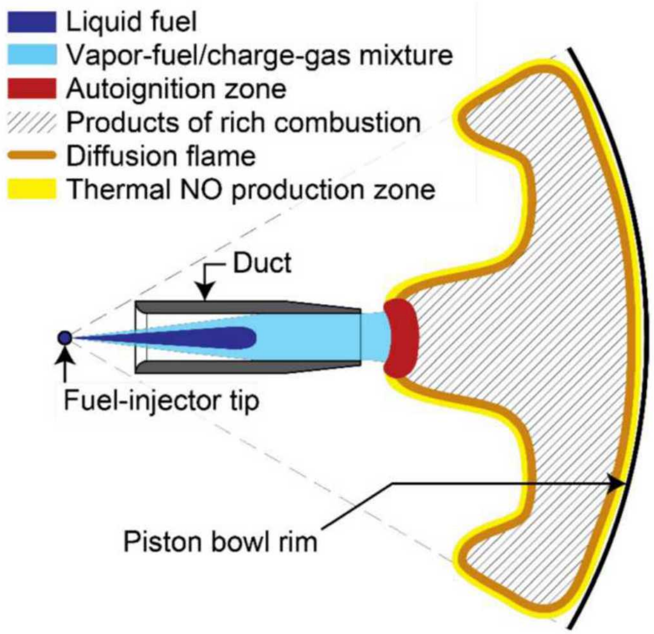
Higher load CDC vs. DFI

- **SINL is much lower for DFI than CDC**
  - Soot is not nearly as much lower
- **Past studies have shown DFI's soot reduction is greatly reduced by late cycle SINL flare up**
  - This flare up is observed in this study
- **Late production of soot likely limits soot oxidation in cylinder**



Summary

- DFI is effective at attenuating engine-out soot emissions across a load range from 1 to 10 bar $IMEP_g$.
- DFI has been observed to break the soot/NO_x trade-off with dilution at low-load conditions.
- DFI allows for both low soot and NO_x levels that are not achievable with CDC at low-load conditions.



Conclusions

- DFI has been shown to attenuate soot formation across a wide range of conditions
- DFI breaks the soot/NO_x tradeoff with dilution
- DFI enhances mixing compared to free spray
- At some conditions DFI has achieved road legal emissions for soot and NO_x at the same time