Sources of CO and UHC Emissions in Low-Temperature Diesel Combustion Systems

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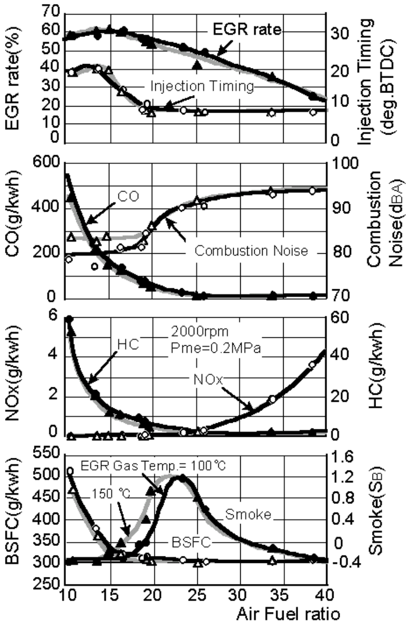
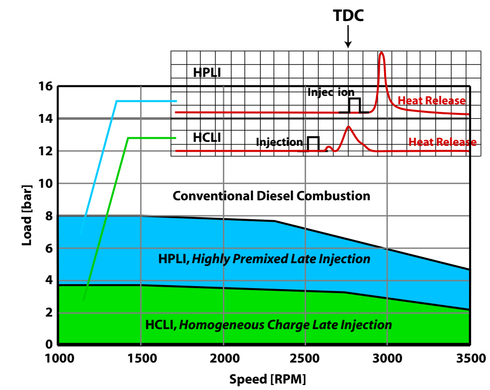
We focus on early-injection, PCI-like combustion systems

Toyota "smokeless" combustion (SAE 2001-01-0655)



Low-temperature combustion systems are attractive because:

- Low NO_X and PM emissions are obtained simultaneously
- They employ typical diesel combustion system FIE & Bowl geometry
- Combustion timing is controlled by the injection event



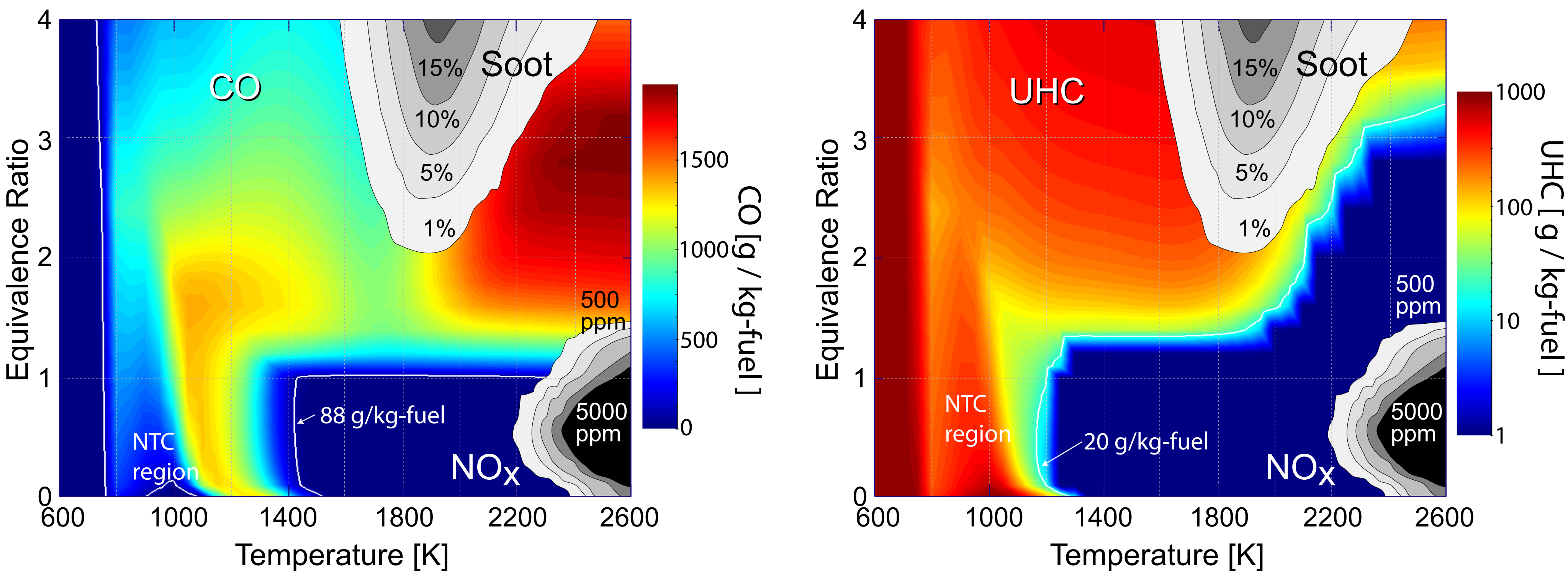
AVL HCLI systems (MTZ, Sept 2003)

However:

- They often suffer from a fuel economy penalty associated with high CO and UHC emissions
- They are applicable over only a limited speed/load range

CO and UHC emissions can stem from cool, fuel-lean regions as well as fuel rich regions

Constant ϕ & T, P = 60 bar, Δt=2 ms, 21% O_2
Soot/NOx contours from Kitamura, et al., JER 3, 2002

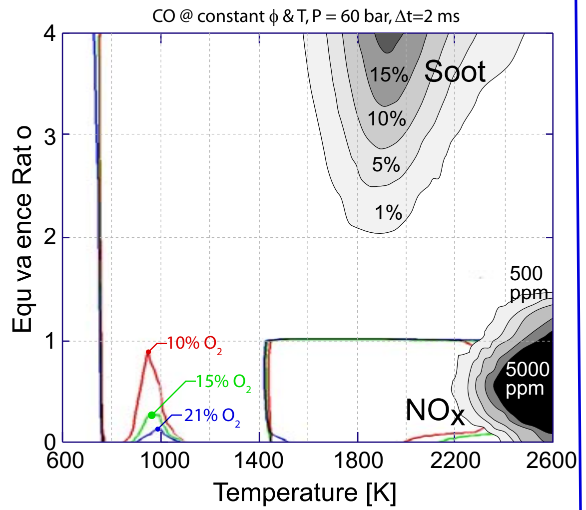


- Low UHC can result even from over-rich regions
- For lean mixtures, temperatures above 1500 K (1300 K) will fully oxidize CO (UHC)
- UHC also stems from cool (T < 800 K) regions at all equivalence ratios

How will EGR influence the kinetics of CO and UHC oxidation?

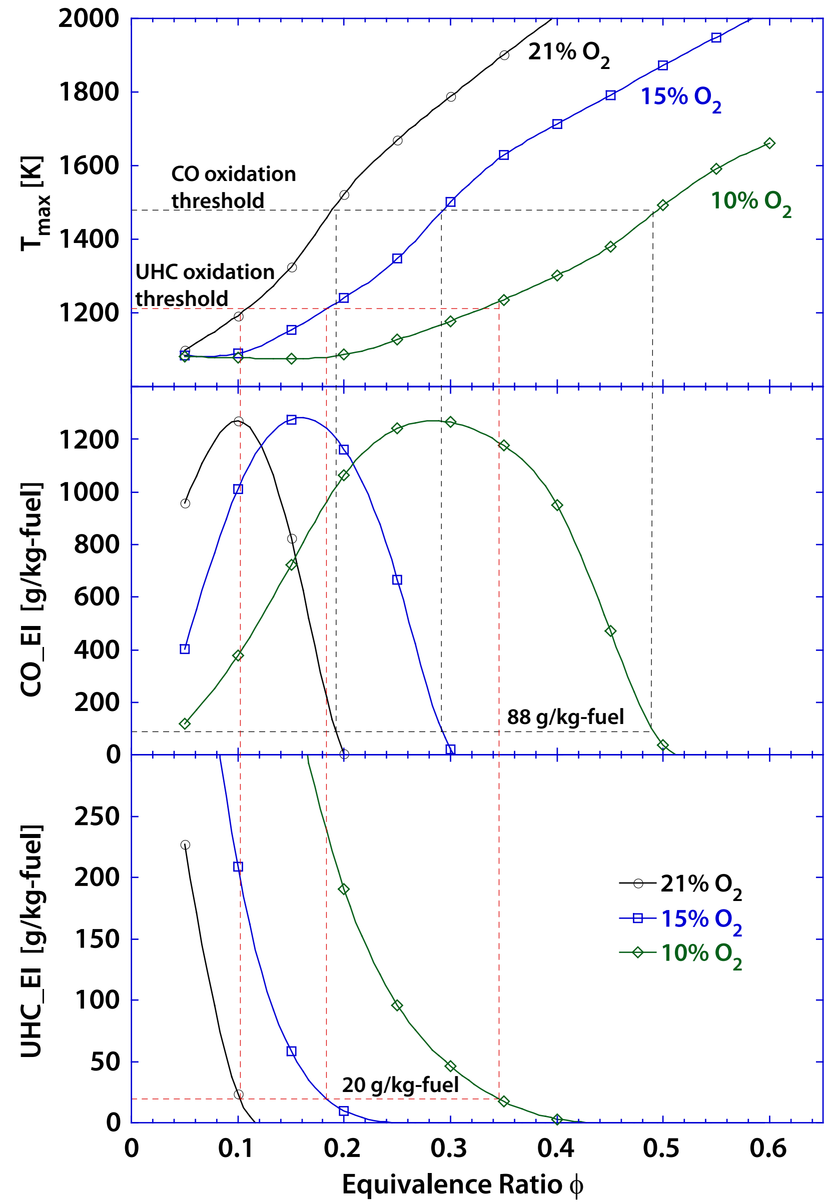
EGR hardly impacts CO yield from constant T, P simulations

CO emissions impacted only in low-temperature crevice regions



The isothermal constraint prevents heat release from raising the temperature and increasing the heat release rate

An adiabatic treatment (with pressure matched to experiment) is more representative of regions away from walls



- The peak temperature needed to oxidize UHC & CO is independent of dilution
- Dilution significantly increases the equivalence ratio needed to reach this temperature

Engine & experiment

Bosch CRI2.2 Common Rail FIE

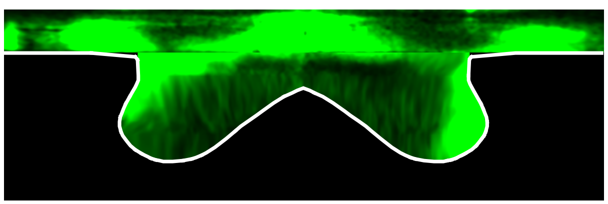
Nozzle	7 hole, 149°, 440 [cm^3 / 30 s]
Rail Pressure	860 bar
Fuel	US #2 diesel fuel

GM 1.9ℓ cylinder head

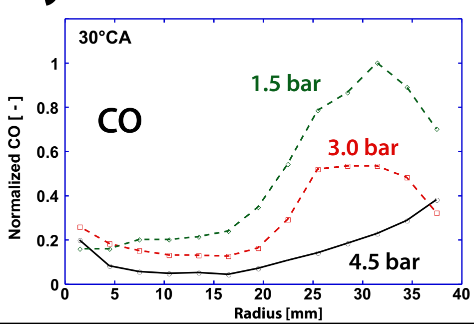
Bore	82.0 mm
Stroke	90.4 mm
Geometric CR	16.7
Effective CR	14.0

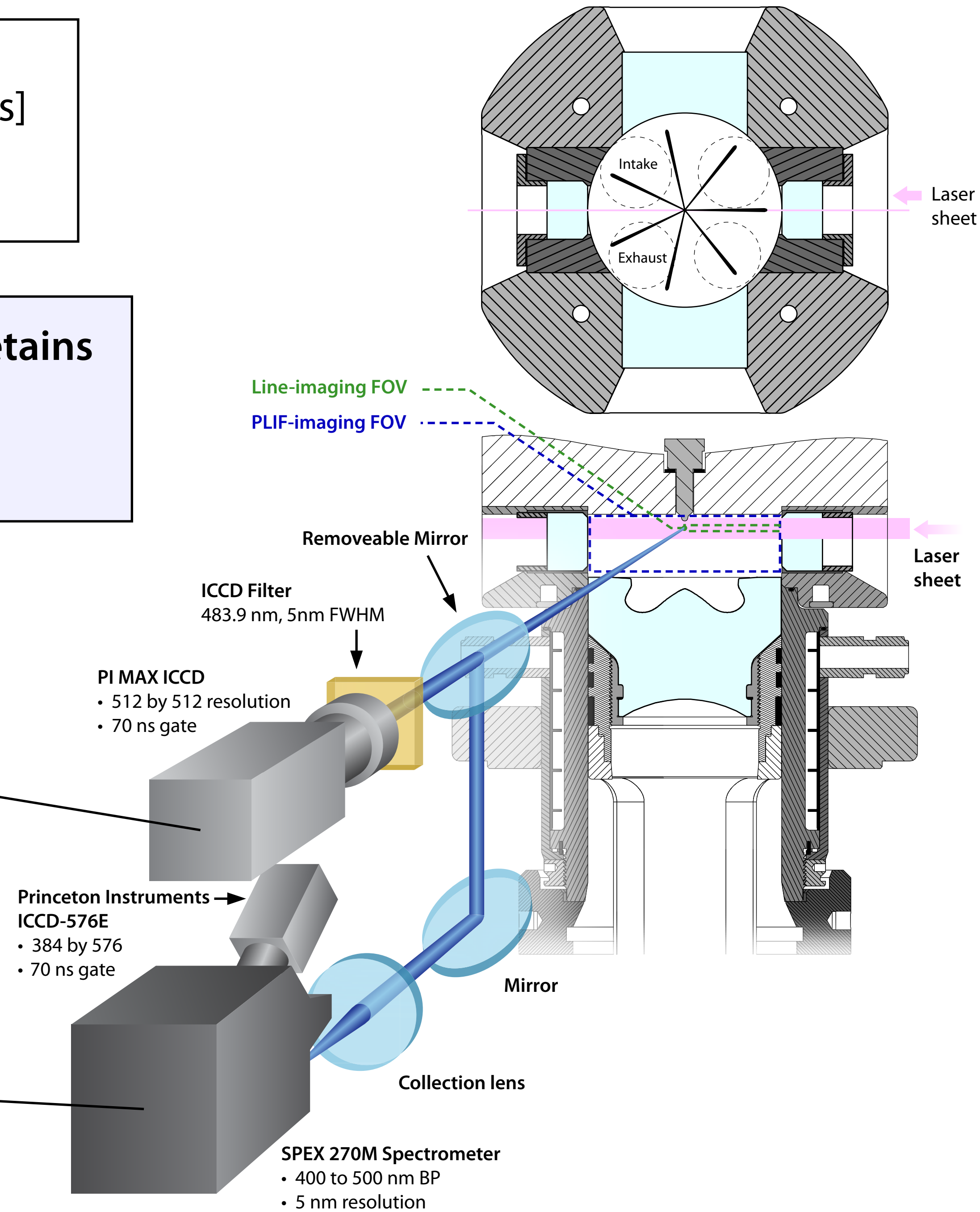
Optical piston retains prototype GM-designed bowl

2-d PLIF Images:

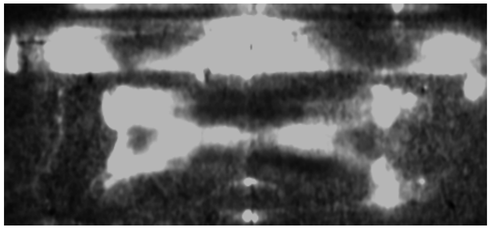


1-d, spectrally-resolved:



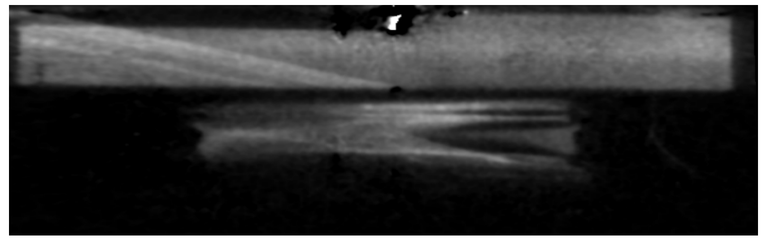


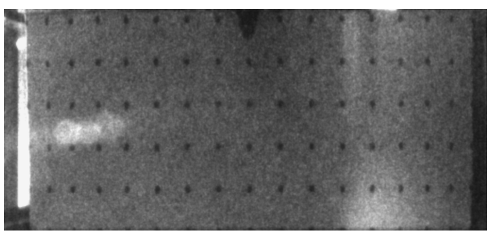
Experimental PLIF images are corrected for distortion and laser sheet inhomogeneity



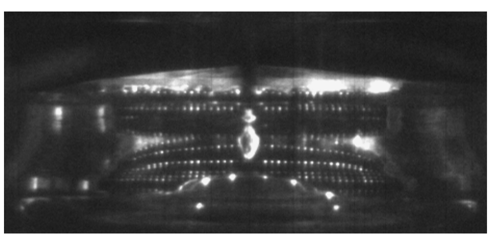
Before correction

A flat-field correction also accounts for laser sheet intensity variation

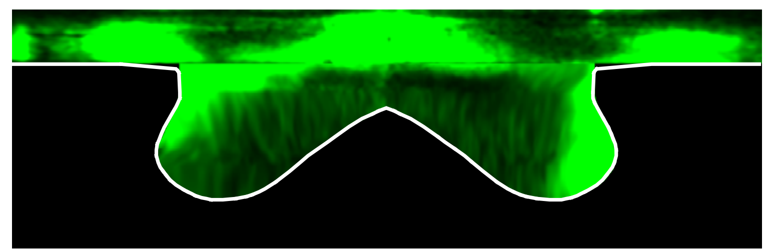




Clearance volume reference grid



Back-lit bowl reference grid



After correction a near seamless image is obtained

Reference grid images in both the clearance volume and the bowl obtained at each crank angle allow separate distortion corrections for both images

Numerical simulations – background

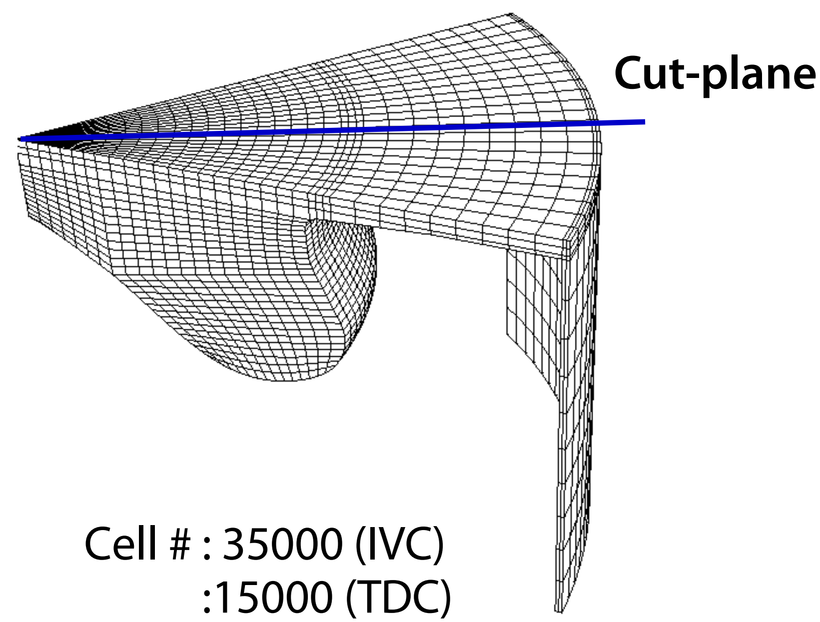
KIVA release 2 coupled with Chemkin chemistry solver

Ignition/combustion model	Chemkin chemistry solver
Mechanism	ERC-PRF mechanism (39 species, 131 reactions)
NOx mechanism	Reduced GRI mechanism (4 species, 9 reactions)
Soot model	2-step phenomenological model
Turbulence model	RNG k-ε model
Atomization/breakup model	KH-RT model

ERC grid-size and time-step independent models (ref. SAE 2008-01-0970)

Liquid/Gas phase momentum coupling	Gas-jet model
Collision/Coalescence model	Radius-of-influence collision model
Time-step calculation	Mean collision time step model
Parcel number control	Re-group model

Computational grid at TDC:

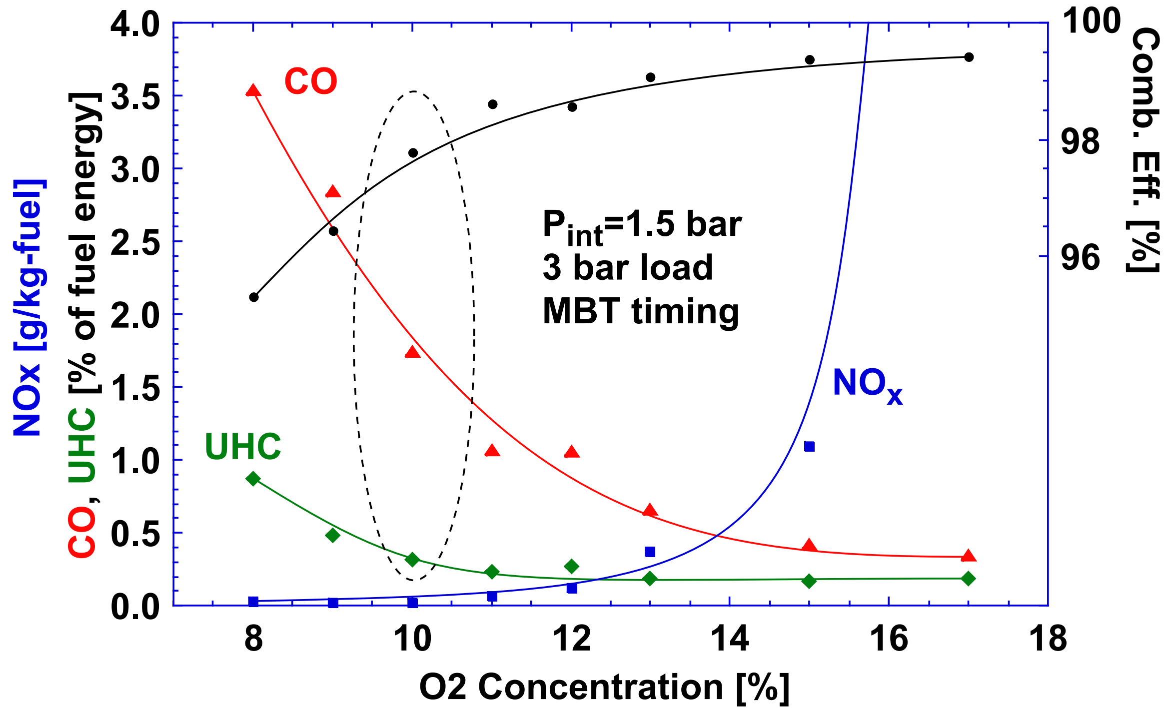


Cell # : 35000 (IVC)
:15000 (TDC)

Operating conditions

We focus on a dilute operating condition with rising CO and UHC emissions, but reasonable combustion efficiency (≈ 98%)

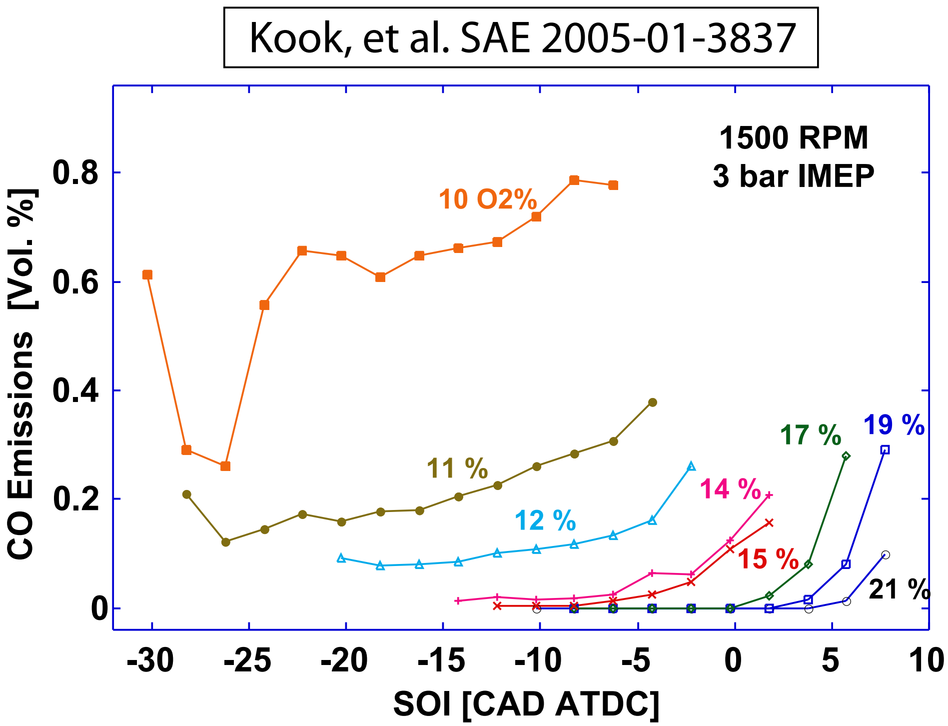
$$\phi_{global} = 0.36$$

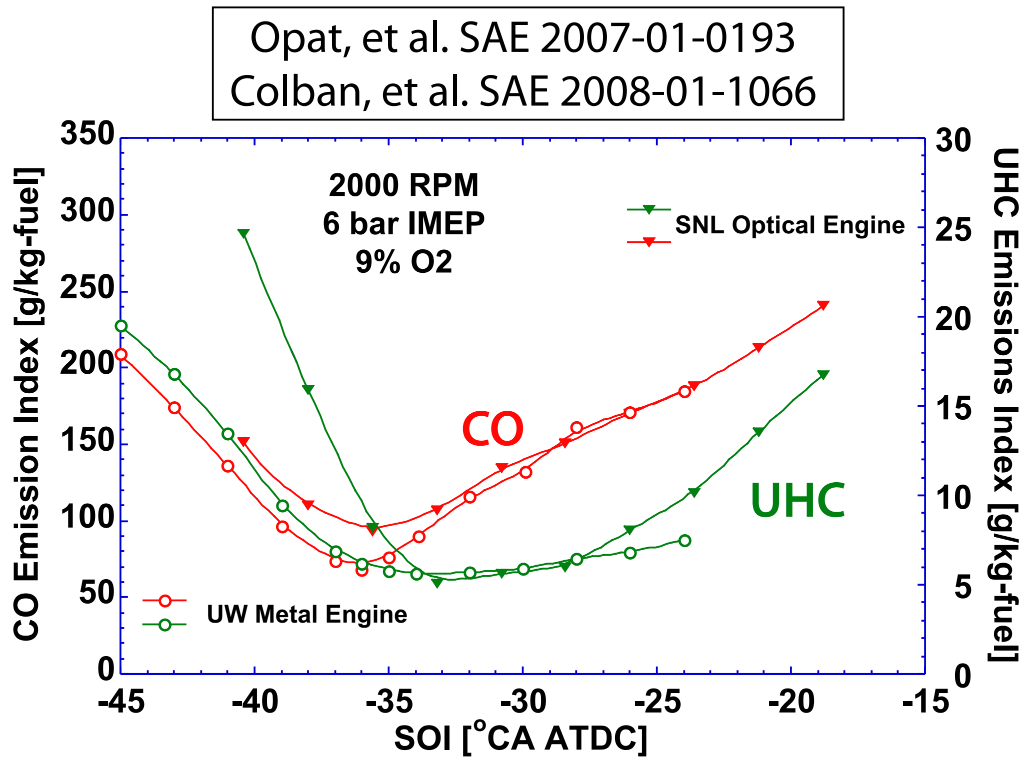


- Three injection timings:
  - "Advanced" = -31.1°
  - "Baseline" (MBT) = -26.6°
  - "Retarded" = -15.8°
- Three loads are also considered

Speed	1500	[rpm]
Load	1.5 – **3.0** – 4.5	[bar]
Intake [O_2]	10.0	[%]
SOI (command)	(-31.1) – (**-26.6**) – (-15.8)	[° ATDC]
T_{intake}	95	[°C]
P_{intake}	1.5	[bar]

An optimal injection timing exists that minimizes CO, UHC, and fuel consumption

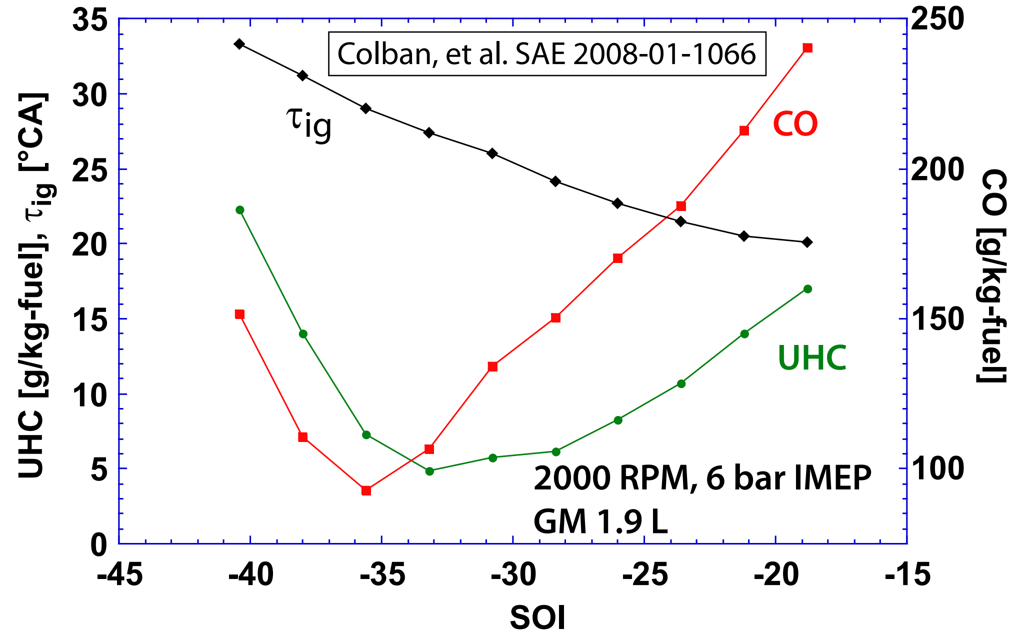




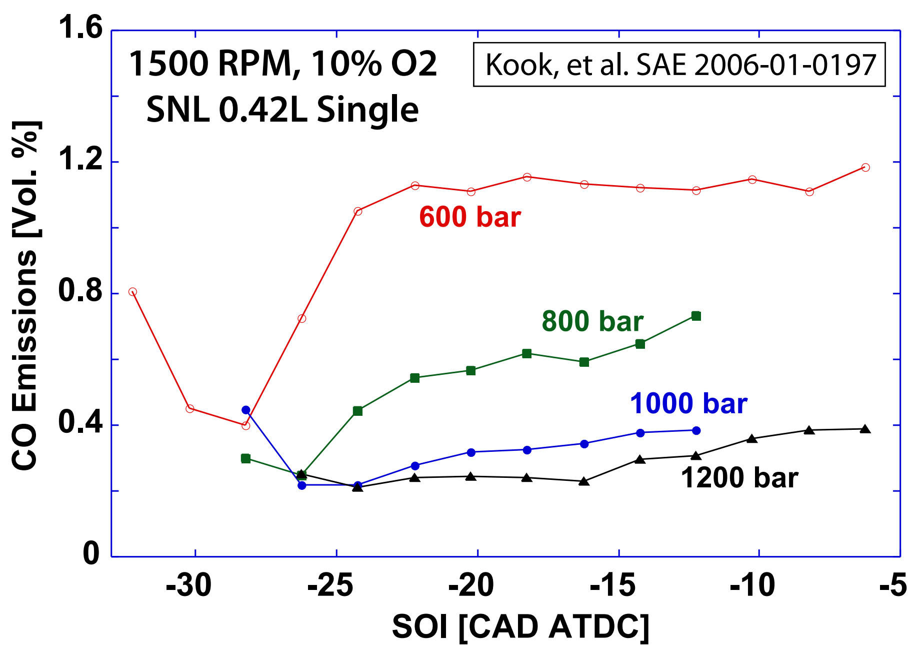
- The existence of this optimum demonstrates the importance (and) variability) of mixing processes)
- This behavior has been duplicated in multiple engine geometries at) various loads)
- Optical engine emissions match metal engine emissions well

Considerable evidence suggests CO and UHC emissions are dominated by fuel-rich regions (mixing-limited)

For SOI retarded from MBT timing, CO and UHC correlate inversely with ignition delay



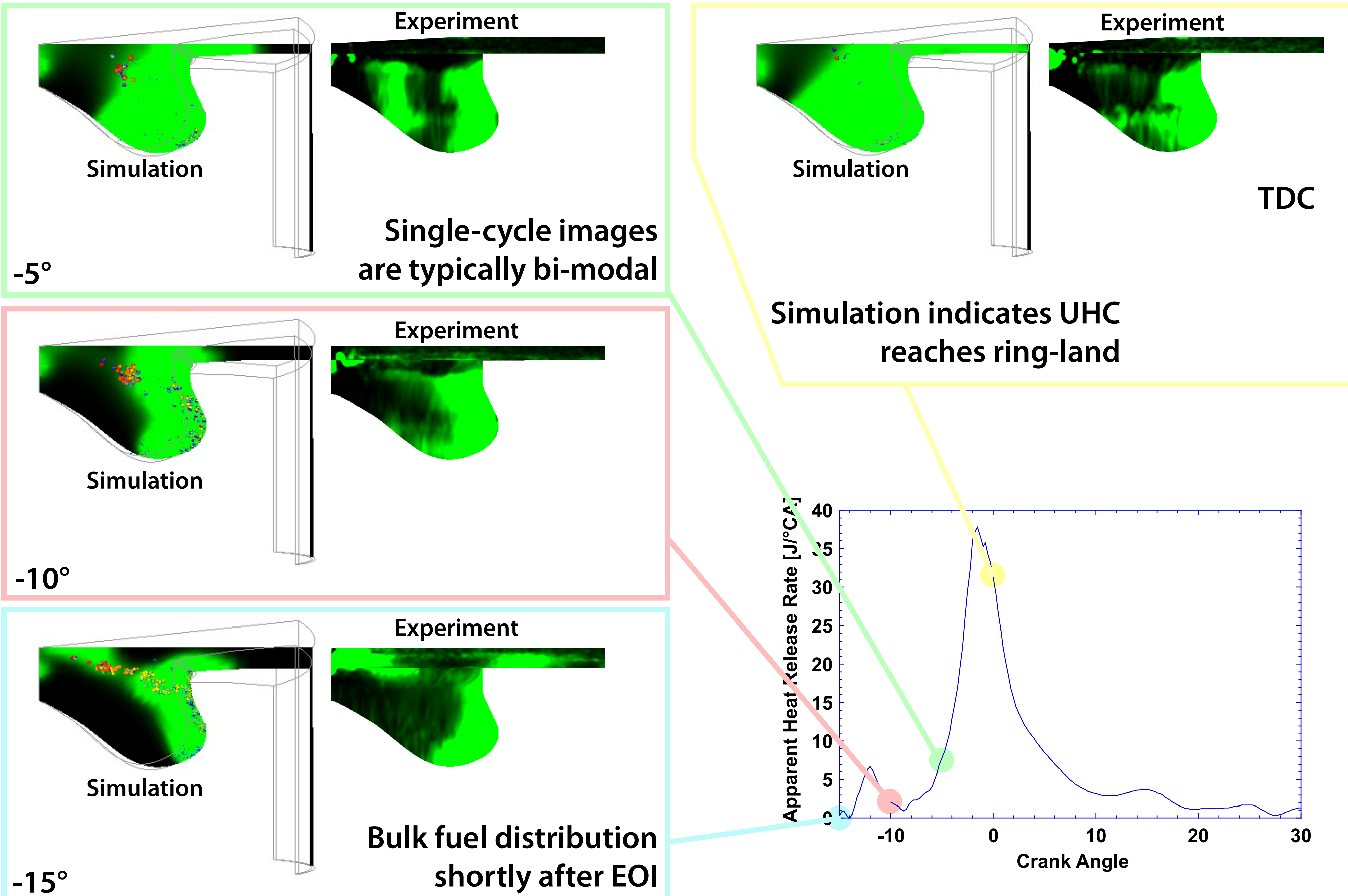
Improved emissions with additional mixing time is inconsistent with CO and UHC stemming from over-lean mixtures



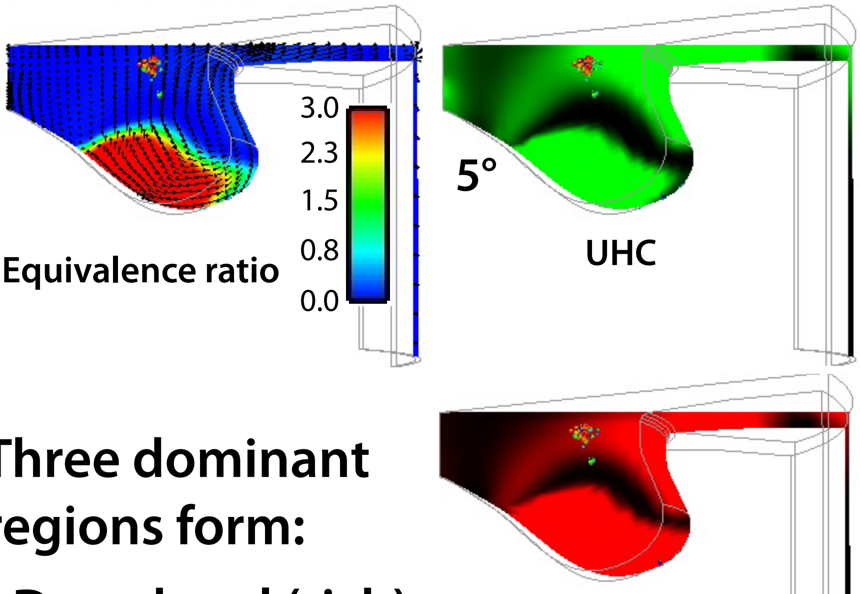
- Enhanced mixing associated with increased P_{inj} reduces CO
  (Similar results reported by Opat, et al. SAE 2007-01-0193)

- Little impact of T_{in} on CO emissions *at the minimum*
  (Opat, et al. SAE 2007-01-0193)

Numerical simulations and in-cylinder measurements clarify the spatial distributions of UHC

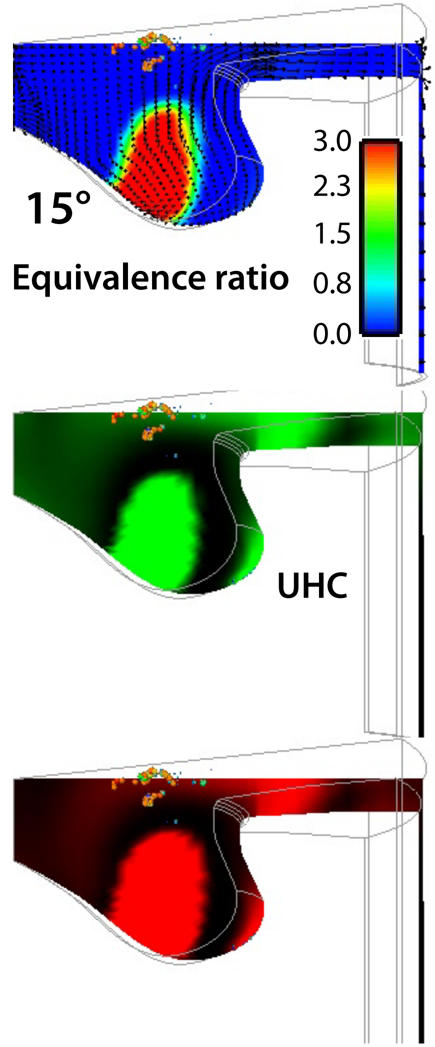


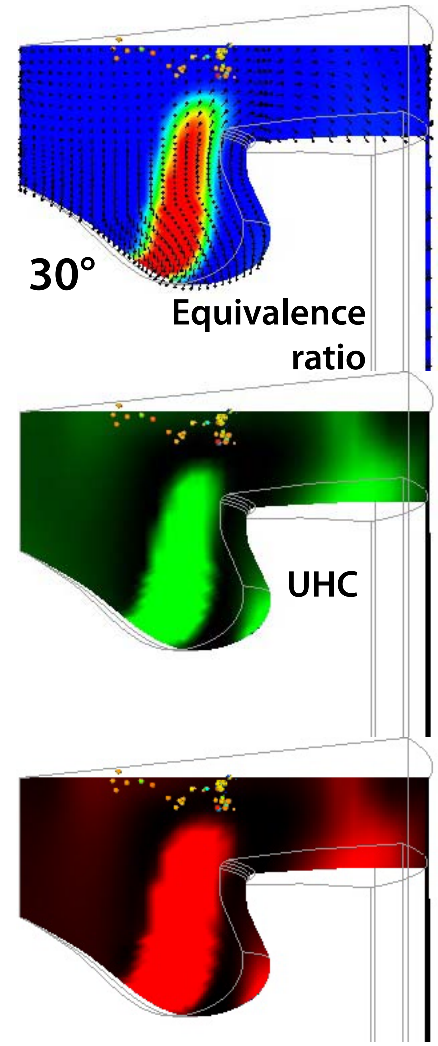
Simulation results show that UHC (and CO) become separated into distinct 'rich' and 'lean' regions

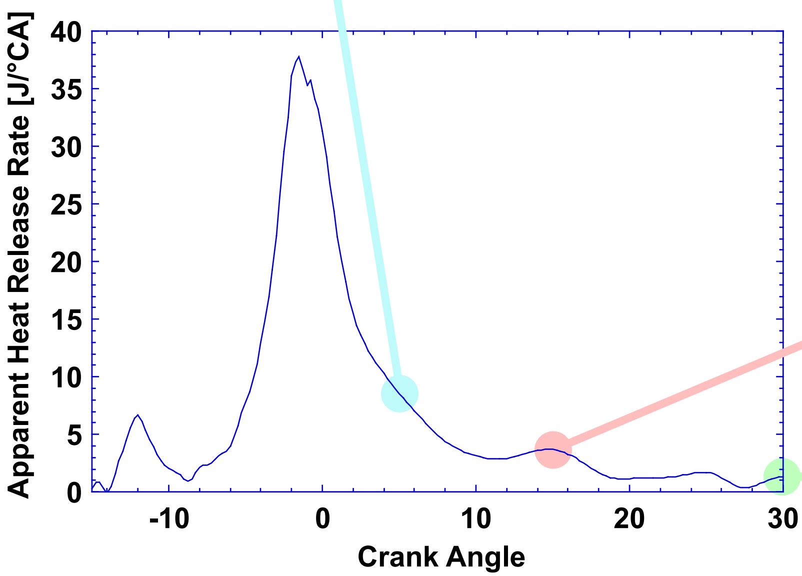


Three dominant regions form:

- Deep bowl (rich)
- Centerline and squish area (lean)





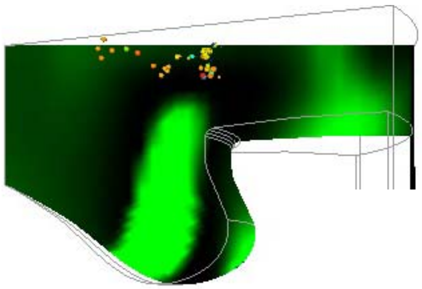


These separate regions persist throughout the remainder of the cycle

(see also Cook, et al. SAE 2008-01-1666)

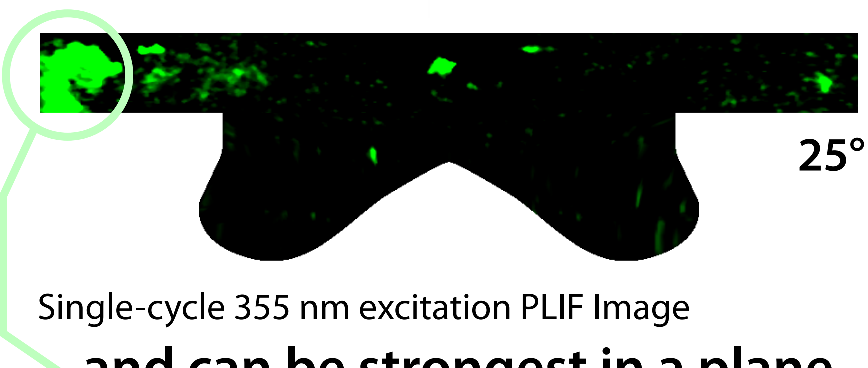
Experiments provide support for the simulated late-cycle UHC and CO distributions

UHC is observed in the ring-land crevice and centerline regions:



Experiment

50-cycle average 230.18 nm excitation PLIF Image (no imaging in bowl)

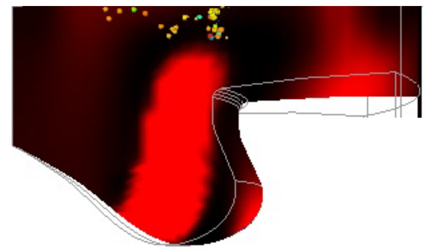


Single-cycle 355 nm excitation PLIF Image

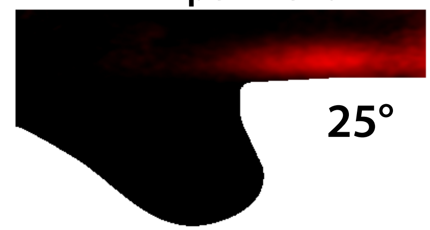
and can be strongest in a plane bisecting the sprays

> **LIF-signal spectral characteristics near the crevice and injector are consistent with largely undecomposed fuel**

CO is observed distributed throughout the (fuel-lean) squish volume:



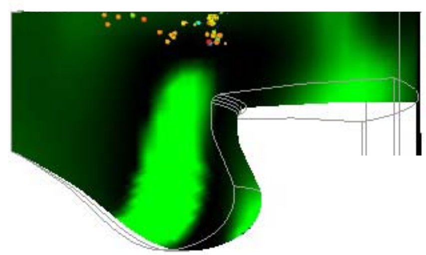
Experiment

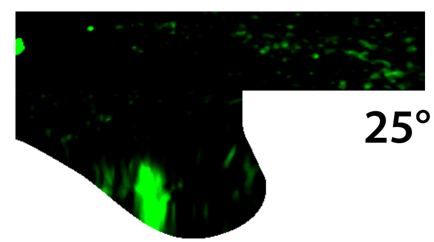


50-cycle average 230.09 nm excitation less offline 230.18 image (no imaging in bowl)

UHC is seen in the lower central region of the bowl...

...but not on all cycles

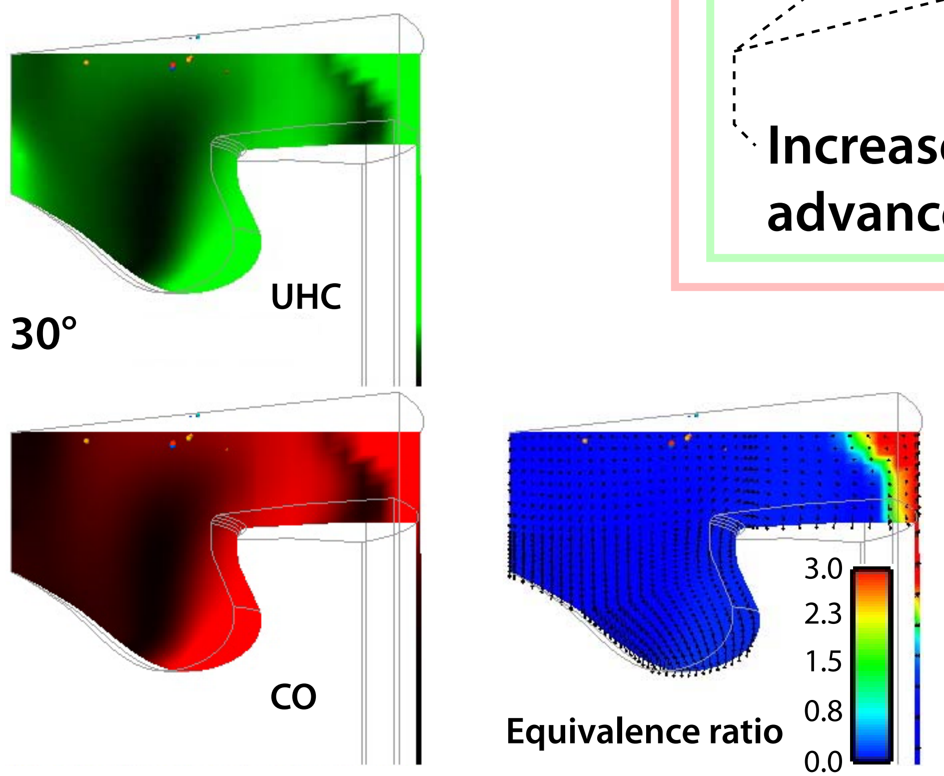




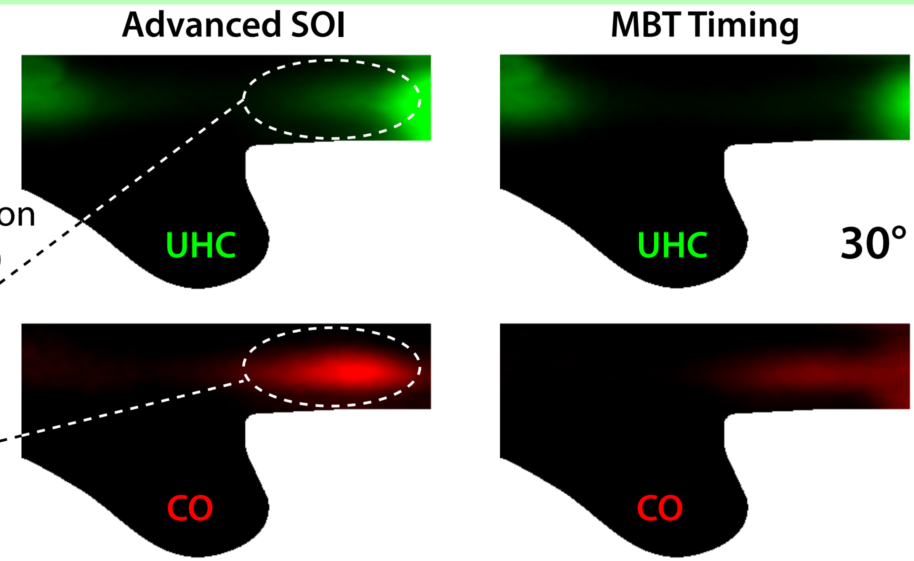
Indicating that rich UHC sources may be less important than the simulations suggest

With advanced SOI, the squish volume becomes fuel-rich, and the bowl lean throughout

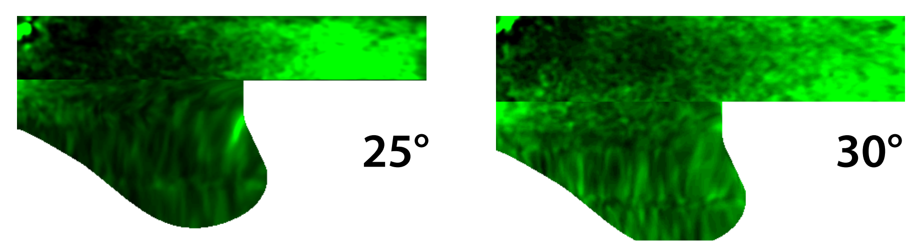
Simulations indicate that UHC and CO emissions stemming from the squish volume dominate



50-cycle average near 230 nm excitation (no imaging in bowl)



Increased squish volume CO and UHC seen with advanced SOI is only consistent with rich mixture

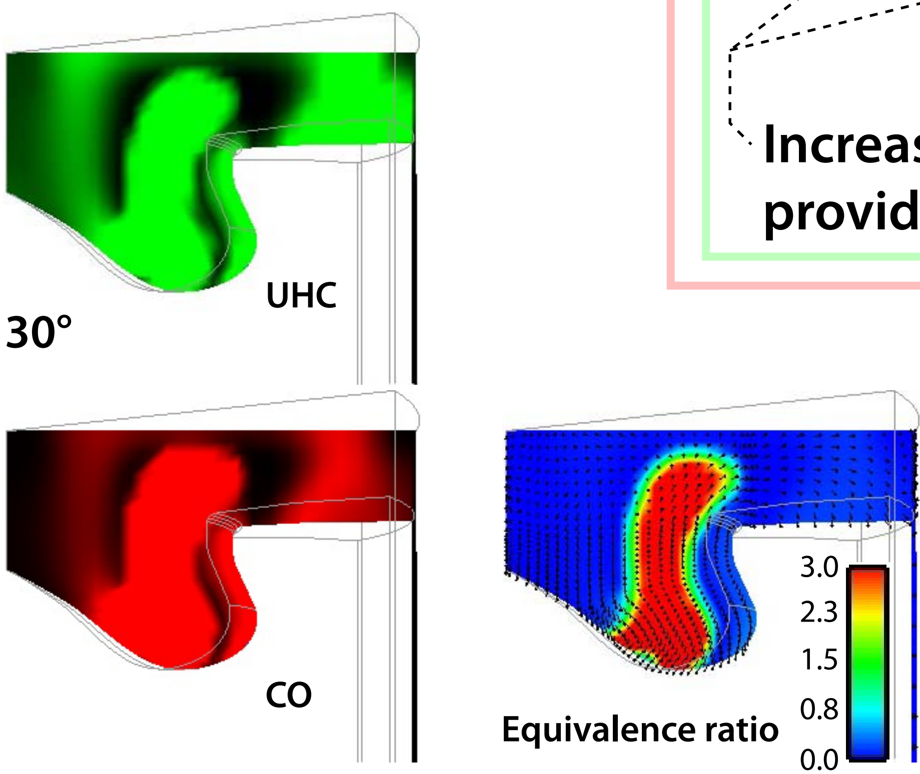


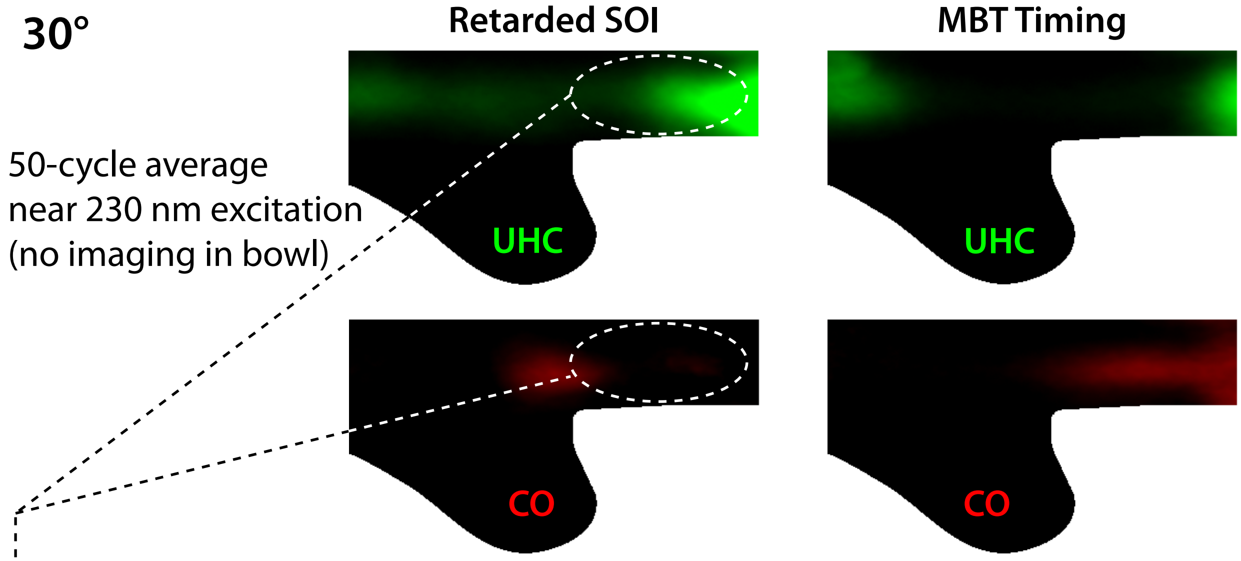
50-cycle average, 355 nm excitation

Only diffuse, low UHC fluorescence is observed within the bowl

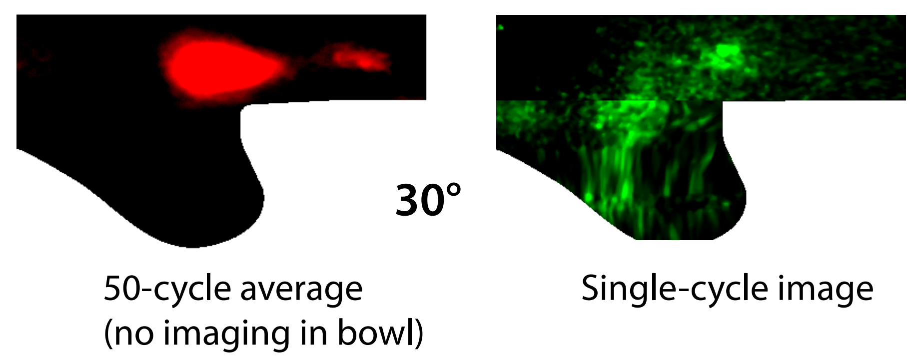
Conversely, with retarded SOI the squish volume is over-lean and regions of the bowl over-rich

Simulations indicate that increased UHC and CO emissions stem from both the squish volume and the bowl



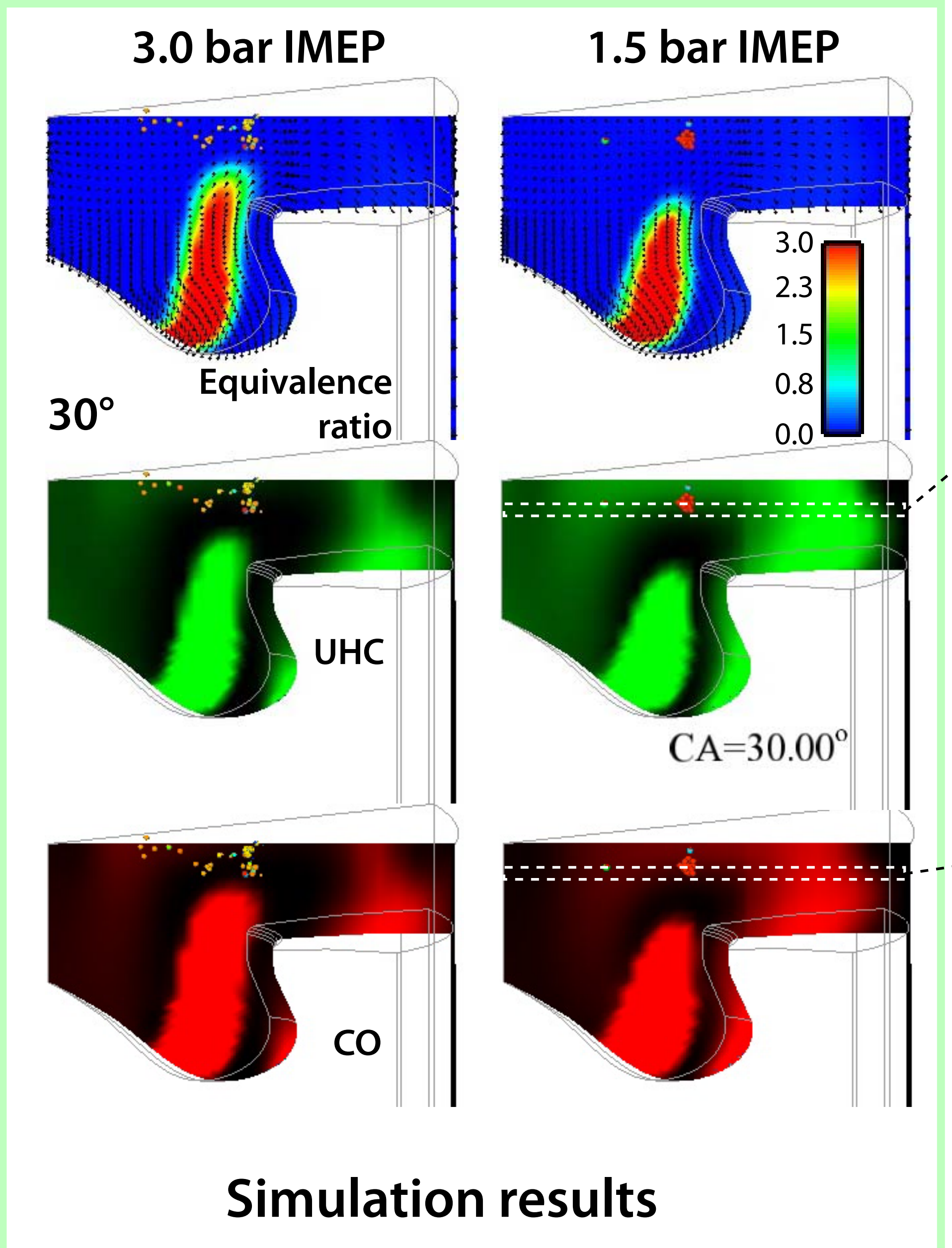


Increased squish volume UHC with decreased CO provides evidence supporting over-lean mixtures

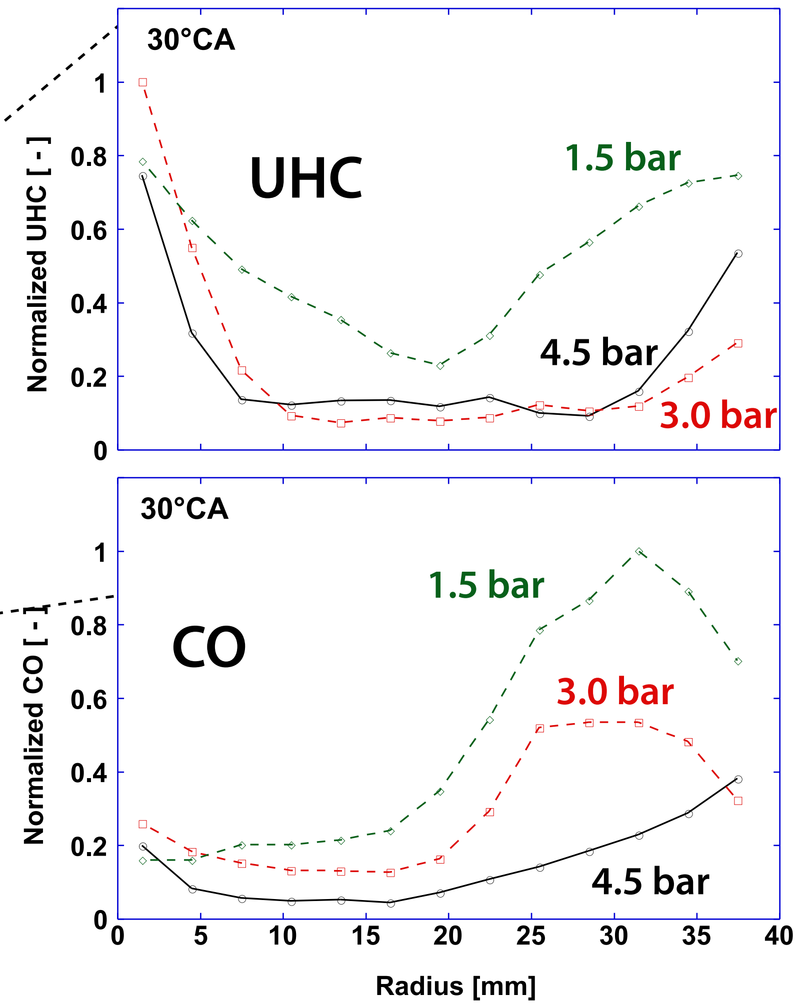


CO and UHC PLIF images both support the simulated distributions

As load decreases, simulations show that the importance of lean emissions from the squish region increases

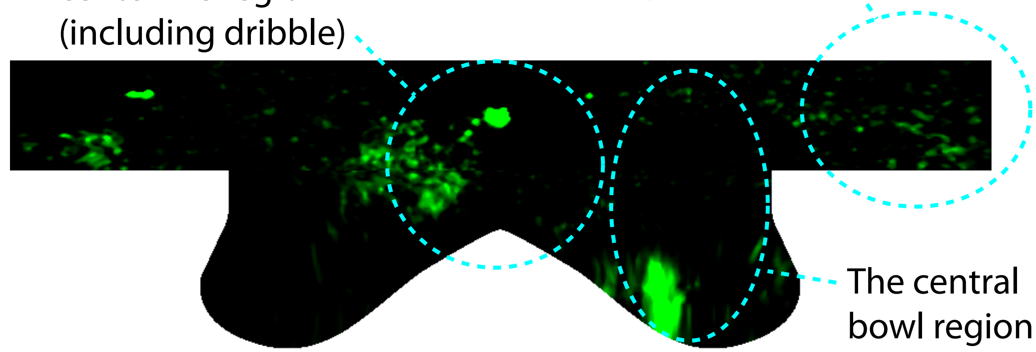


Measured radial profiles of UHC and CO fluorescence signal support this finding:



Recap (and redress)

UHC and CO emissions from PCI-like combustion systems are found to stem from three main regions of the cylinder.



- **Both simulations and experiments indicate that emissions from the squish and) bowl regions will dominate**
- **The squish or bowl regions can be either fuel-rich or fuel-lean, depending on the operating condition (injection timing, load, etc.)**
- **(At MBT timing, an optimal fuel distribution is achieved that results in a not-too-rich bowl region and a not-too-lean squish region. Simulations indicate emissions stem almost equally from these regions**
- **With lighter load (or retarded SOI), emissions from the lean squish area become more pronounced** (increased T_{in}, high pressure EGR, VVA, decreased EGR)
- **(At higher load, emissions from the rich bowl come to dominate** (increase mixing)