Mixture Formation in a Light-Duty Diesel Engine

Paul C. Miles, Benjamin R. Petersen, Dipankar Sahoo

Sandia National Laboratories

Livermore, CA USA

Directions in Engine-Efficiency and Emissions Research

DEER 2012

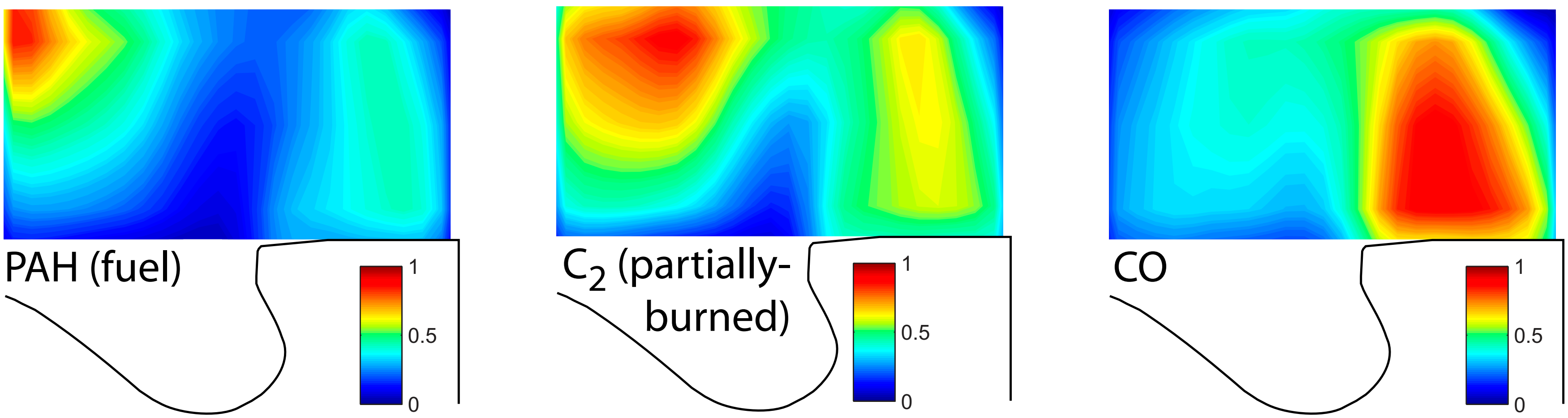
October 15-19, 2012 Dearborn, MI

Acknowledgements: Gurpreet Singh, DOE EERE-OVT

General Motors Corporation

At low-load, UHC and CO emissions under LTC conditions are dominated by lean bulk gas mixture

Measured UHC/CO distributions at 50° aTDC (Deep-UV LIF)

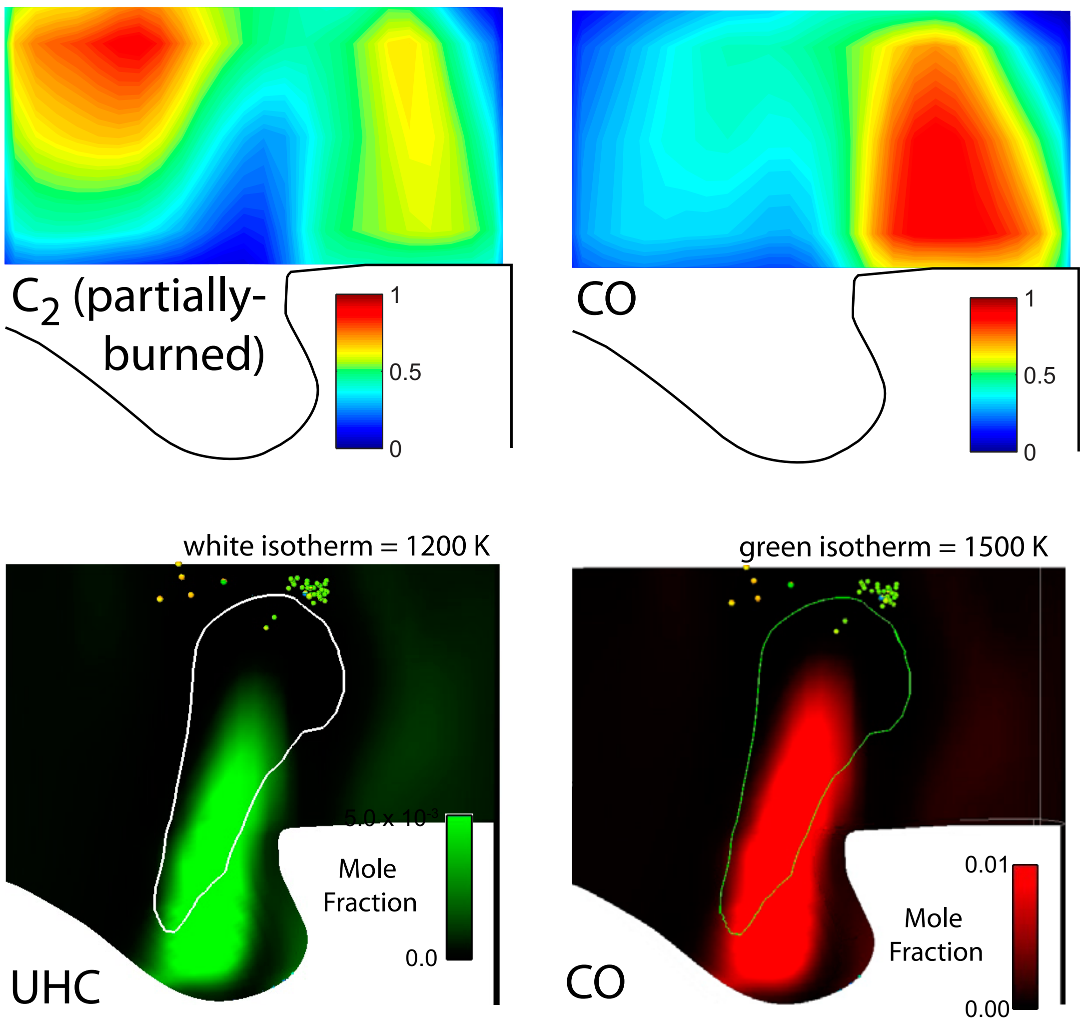


The lean bulk gas mixture is mainly in the squish volume and upper-central cylinder

- ? How is this mixture formed and transported within the cylinder as injection, ? mixing, and combustion proceed?
- ? What are the relative roles of mixture formation and chemical kinetics in creating ? these emissions?
- ? How do these roles change with operating parameters? ?

Comparisons with simulations indicate that fuel-air mixing may not be adequately predicted

Measurements



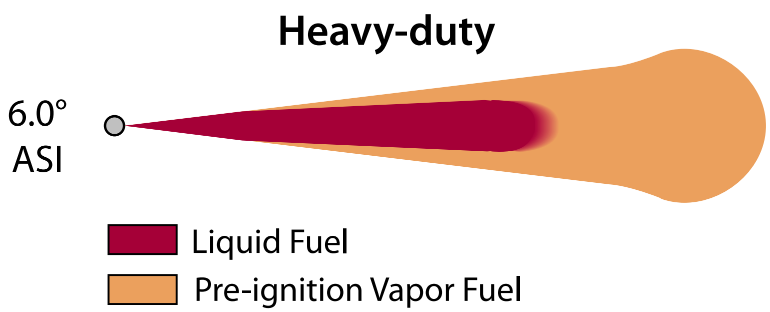
Simulation

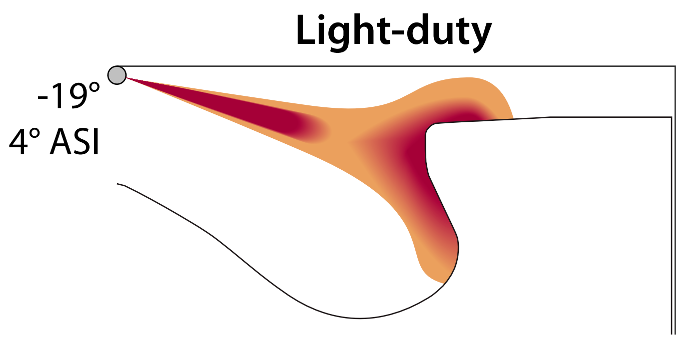
How sensitive are the simulation results to:

- ? Near-nozzle modeling practices?
- ? Grid resolution?
- ? Nozzle geometry / targeting?
- ? Ambient flow (swirl) ?
- ? Injection rate?
- ? Reduced kinetic mechnisms? ?

Mixture preparation has not been studied quantitatively in light-duty engines

The mixture preparation processes in light-duty engines is very different from the "free-jets" characteristic of heavy-duty engines:





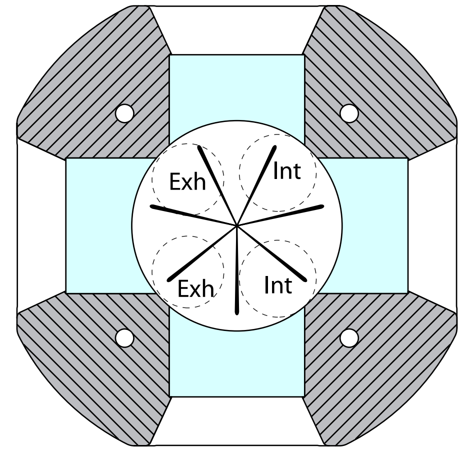
- ? Light-duty engines have strong wall interactions, including liquid phase impingement and re-direction of jet momentum by the piston surfaces
- ? Swirl creates a strong cross-flow which, near TDC, is strongest at the jet stagnation region near the bowl lip

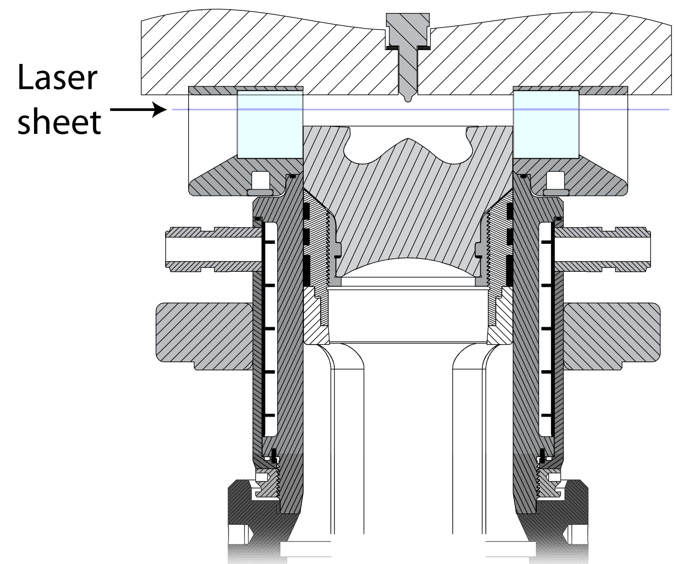
There are no reported quantitative measurements of the fuel-air equivalence ratio distributions in light-duty engines

Engine Facility and Experimental Set-up

Measurements are made in a GM 1.9L optically accessible engine

- Piston geometry has production-like bowl and valve pockets
- Top ring-land crevice approximately 3–4 times volume of production engine crevice
- Gap-less compression rings reduce blowby
- Recessed liner windows allow squish volume access @TDC
- Fluorescence collected through piston





Engine Geometry

Bore	82.0 mm
Stroke	90.4 mm
Displ. Volume	0.477 L
Geometric CR	16.7
Squish Height	0.88 mm

Injector specifications

Injector	Bosch CRI2.2
Nozzle Type	Mini Sac (0.23 mm^3)
Holes	
Nozzle diameter	0.139 mm
Included Angle	149°
Hole geometry	KS1.5/86

Engine Facility and Experimental Set-up

Measurements are made in a GM 1.9L optically accessible engine

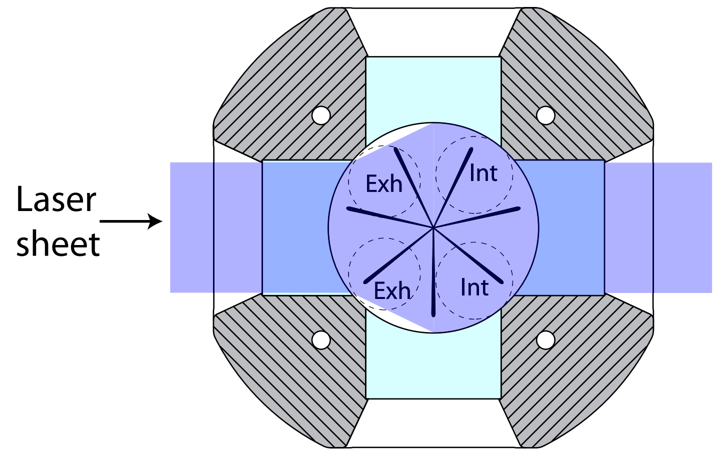
- ?Piston geometry has production-like bowl and ? valve pockets)?
- ?Top ring-land crevice approximately 3–4 times)? volume of production engine crevice?
- ?Gap-less compression rings reduce blowby?
- ?Recessed liner windows allow squish volume ? access @TDC)?
- ?Fluorescence collected through piston)?

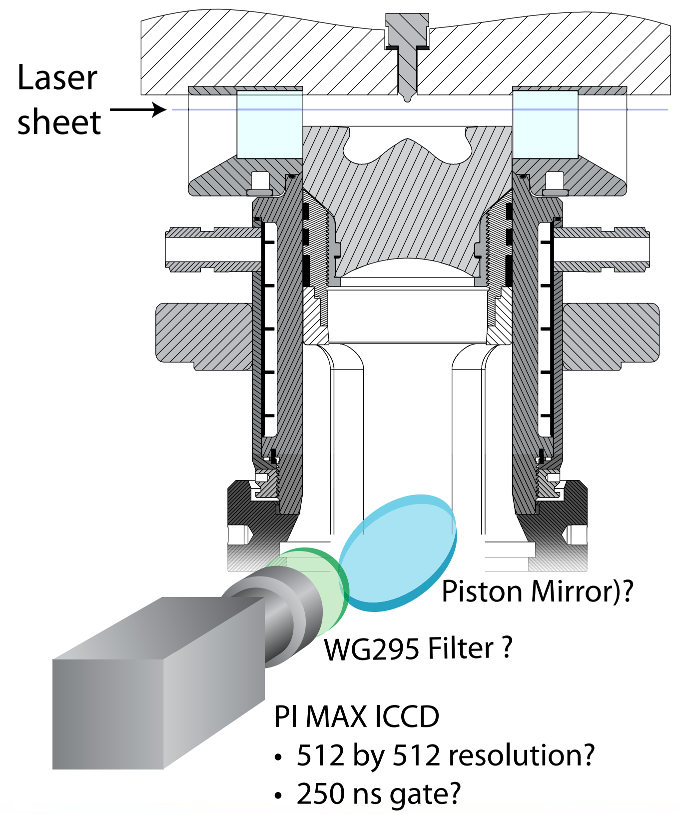
Engine Geometry

Bore	82.0 mm
Stroke	90.4 mm
Displ. Volume	0.477 L
Geometric CR	16.7
Squish Height	0.88 mm

Injector specifications

Injector	Bosch CRI2.2
Nozzle Type	Mini Sac (0.23 mm³)
Holes	
Nozzle diameter	0.139 mm
Included Angle	149°
Hole geometry	KS1.5/86





Operating conditions

Single injection, low temperature 'PCI-like' operation (10% O_2)

Engine speed	1500 rpm
Load	3 bar
Intake Pressure	1.5 bar
Swirl ratio	1.5, 2.2, 3.5, 4.5
Squish Height	0.88 mm
Motored TDC density*	21.1 [kg/m^3]
Motored TDC temperature*	908 [K]
Injected fuel quantity	typically 8.8 mg (single injection)
Global Equivalence Ratio†	0.4
Injection pressure	500, 860, 1220 bar
Start-of-Injection (SOI)	-27.8, -23.4, -12.5°CA aTDC
Injection duration	~ 5.4°CA (600 μs)

* based on GT-Power modeling of the induction and compression stroke

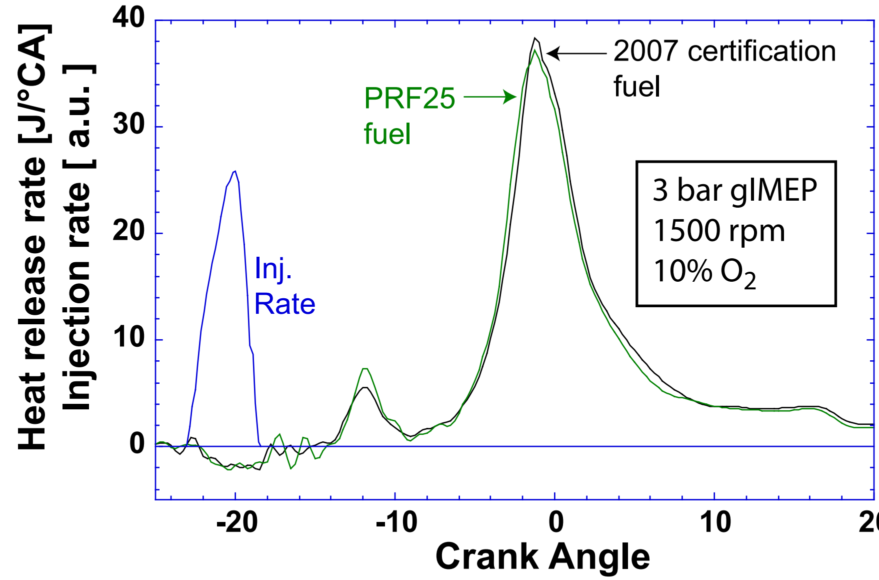
† assumes a 10% O_2 concentration

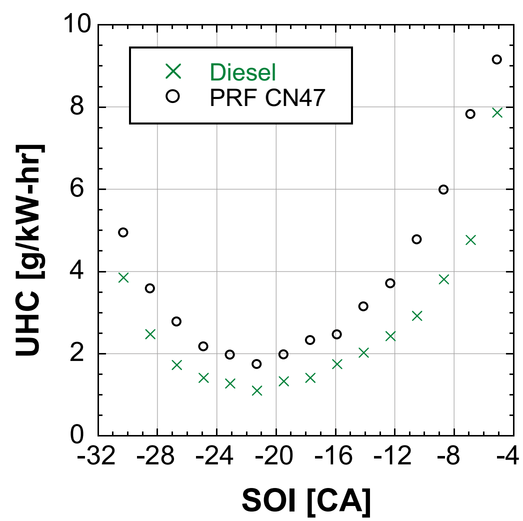
Fuel & Tracer Selection

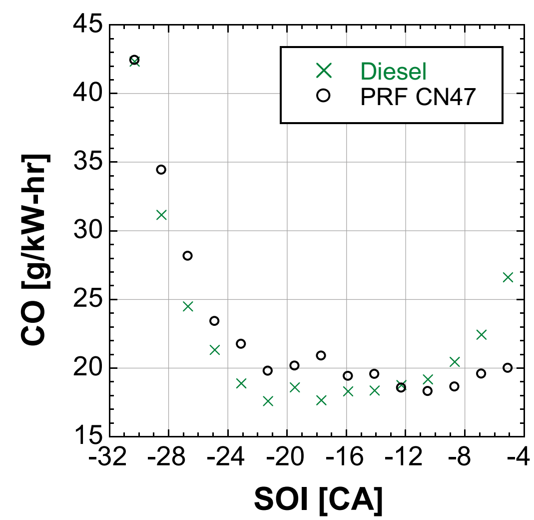
- Diesel fuel unsuitable due to unknown photophysics
- Toluene tracer (0.5%) in PRF25 fluorescence-free base fuel
  - Known photophysics (T, P dependency)
  - Thermal stability
  - Closely matched boiling points

Fuel & Tracer Selection

- Diesel fuel unsuitable due to unknown photophysics
- Toluene tracer (0.5%) in PRF25 fluorescence-free base fuel
  - Known photophysics (T, P dependency)
  - Thermal stability
  - Closely matched boiling points
- Matches combustion phasing, HR and HC/CO emissions of CN47 diesel under early-injection operation

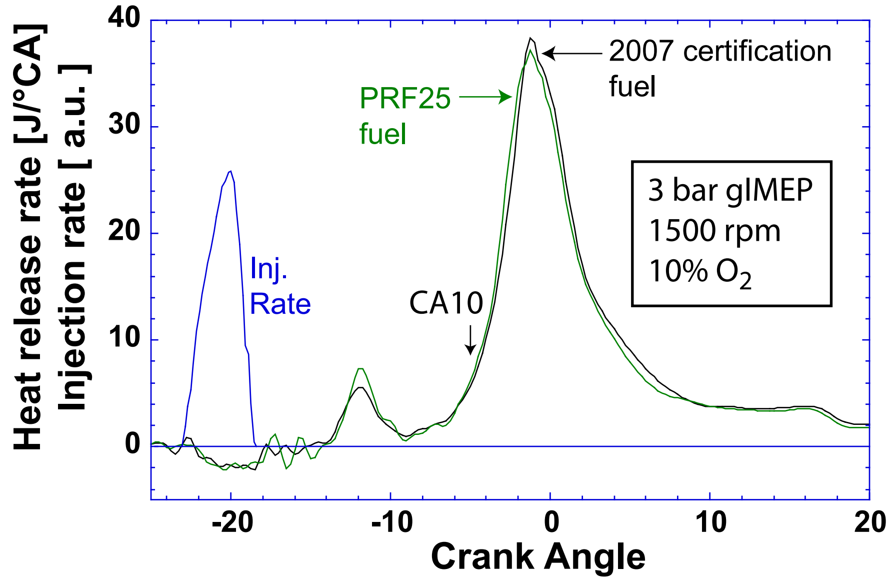


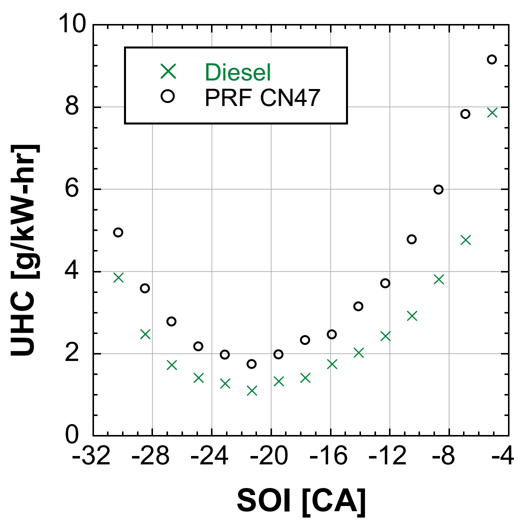




Fuel & Tracer Selection

- Diesel fuel unsuitable due to unknown photophysics
- Toluene tracer (0.5%) in PRF25 fluorescence-free base fuel
  - Known photophysics (T, P dependency)
  - Thermal stability
  - Closely matched boiling points
- Matches combustion phasing, HR and HC/CO emissions of CN47 diesel under early-injection operation
- Measurements made in an N_2 atmosphere (Matched T and ρ)
- Data representative of fired operation through ~ CA10





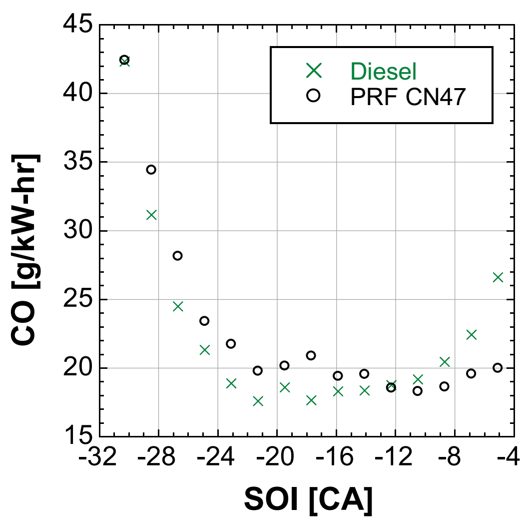
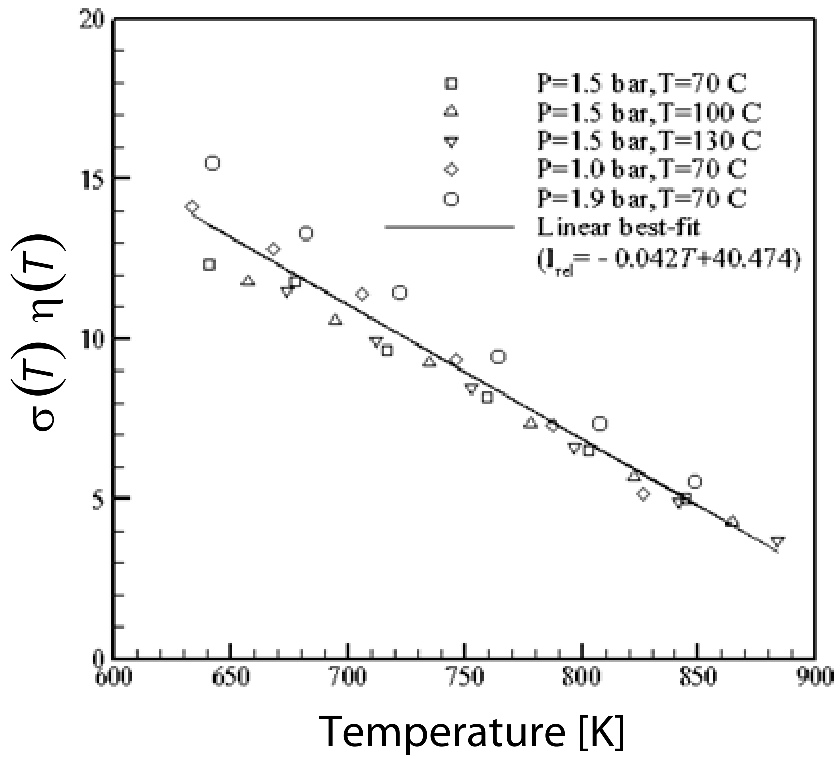


Image Processing Summary

- Data images are corrected for background interference and optical distortion
- "Flat-field" calibration images, obtained in homogeneous mixtures with known χ_{fuel}, further correct for laser sheet inhomogeneity
- Fuel mole fraction is computed from:

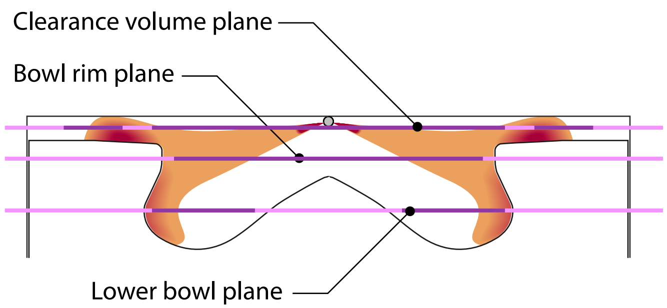
$$\chi_{fuel} = \chi_{fuel,cal} \frac{S_{toluene,d}}{S_{toluene,cal}} \frac{E_{cal}}{E_d} \frac{T_d}{T_{cal}} \frac{P_{cal}}{P_d} \frac{\sigma(T_{cal})\eta(T_{cal})}{\sigma(T_d)} \frac{}{\eta(T_d)}$$

- The product $\sigma(T)\eta(T)$ is determined from *in situ* calibration studies
- With the calculated χ_{fuel}, a local temperature is estimated using an adiabatic mixing model and the χ_{fuel} estimate is refined until convergence is achieved
- Mean images and 'frequency' distributions from single-cycle images are computed



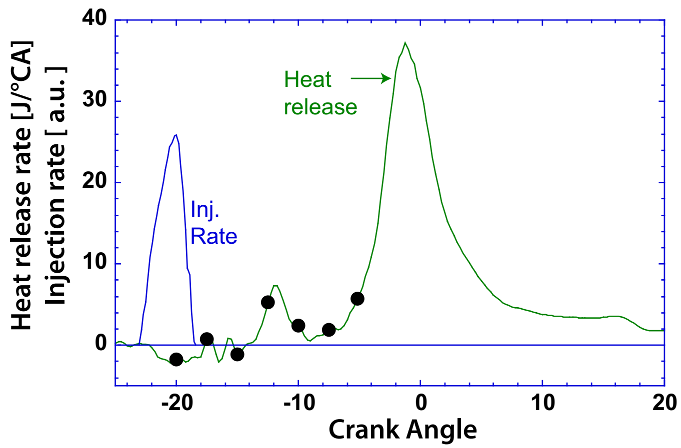
Mixture Preparation Overview
SOI = -23.3°, R_s = 2.2, P_{inj} = 860 bar

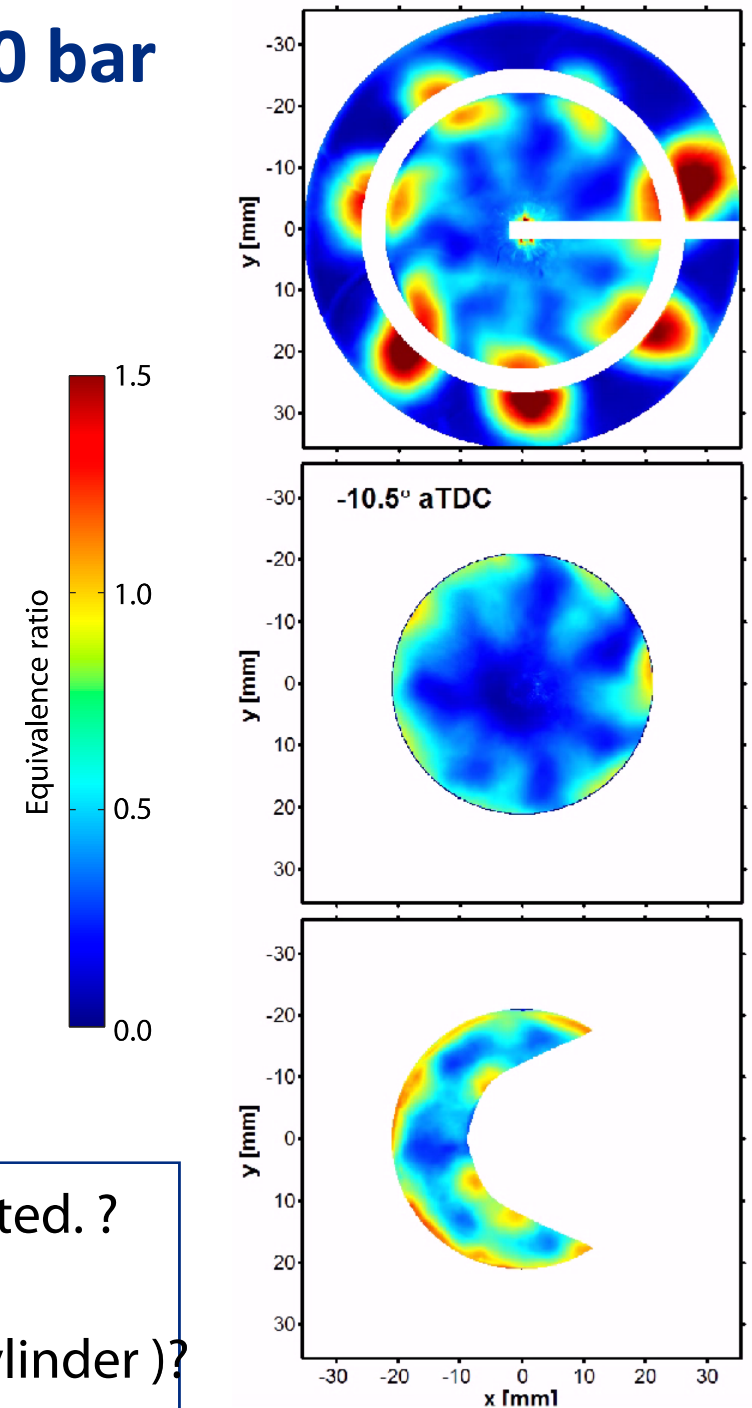
Measurements are made in three planes...



Darkened areas of the laser sheet indicate visible regions

...through the start of HTHR





- The mixture preparation process is clearly illustrated. ? First penetration dominates, then rotation.
- Note the thorough mixing in the upper central cylinder)?

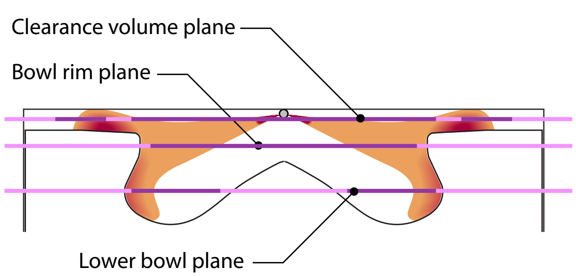
CA10 Mixture Distribution
SOI = -23.3°, R_s = 2.2, P_{inj} = 860 bar

At the start of HTHR:

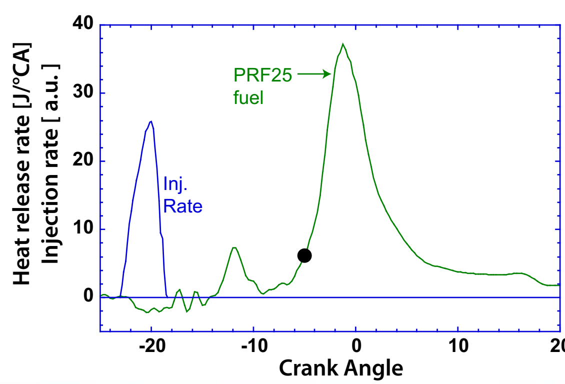
•? Fuel in Plane 1 is near the cylinder walls and will be forced into the ring-land by during high temperature heat release

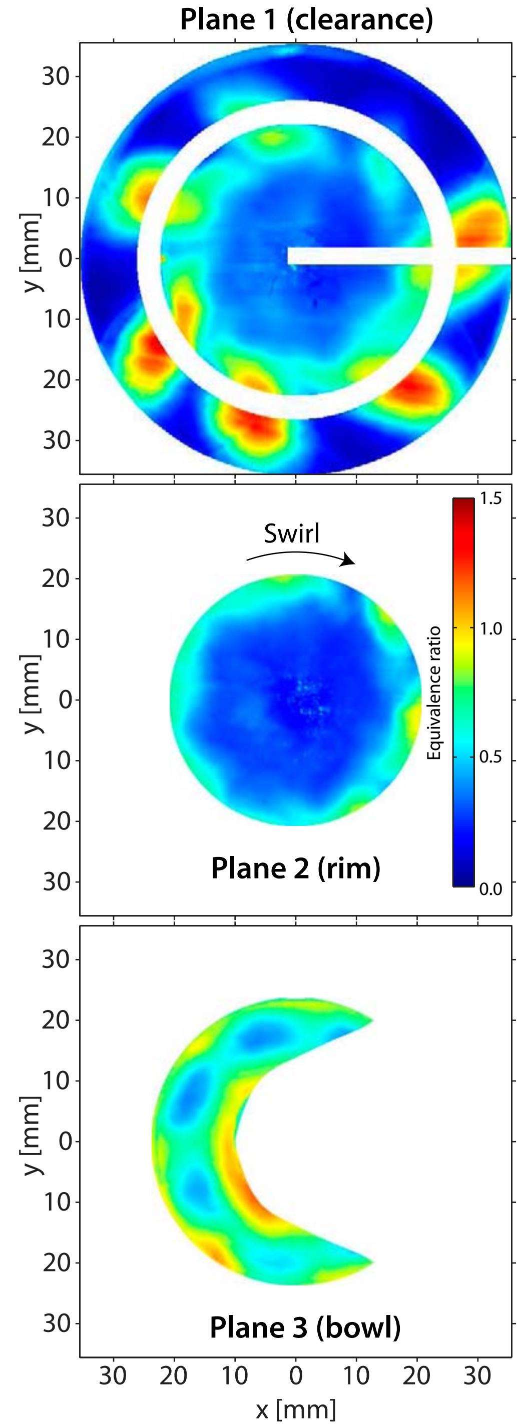
•? Fuel-rich mixtures persist within the squish volume, but <ϕ> is less than 2 (single-cycle images show this also)

•? There is substantial over-lean mixture in the upper-central regions of the bowl and clearance volume.



Darkened areas of the laser sheet indicate visible regions



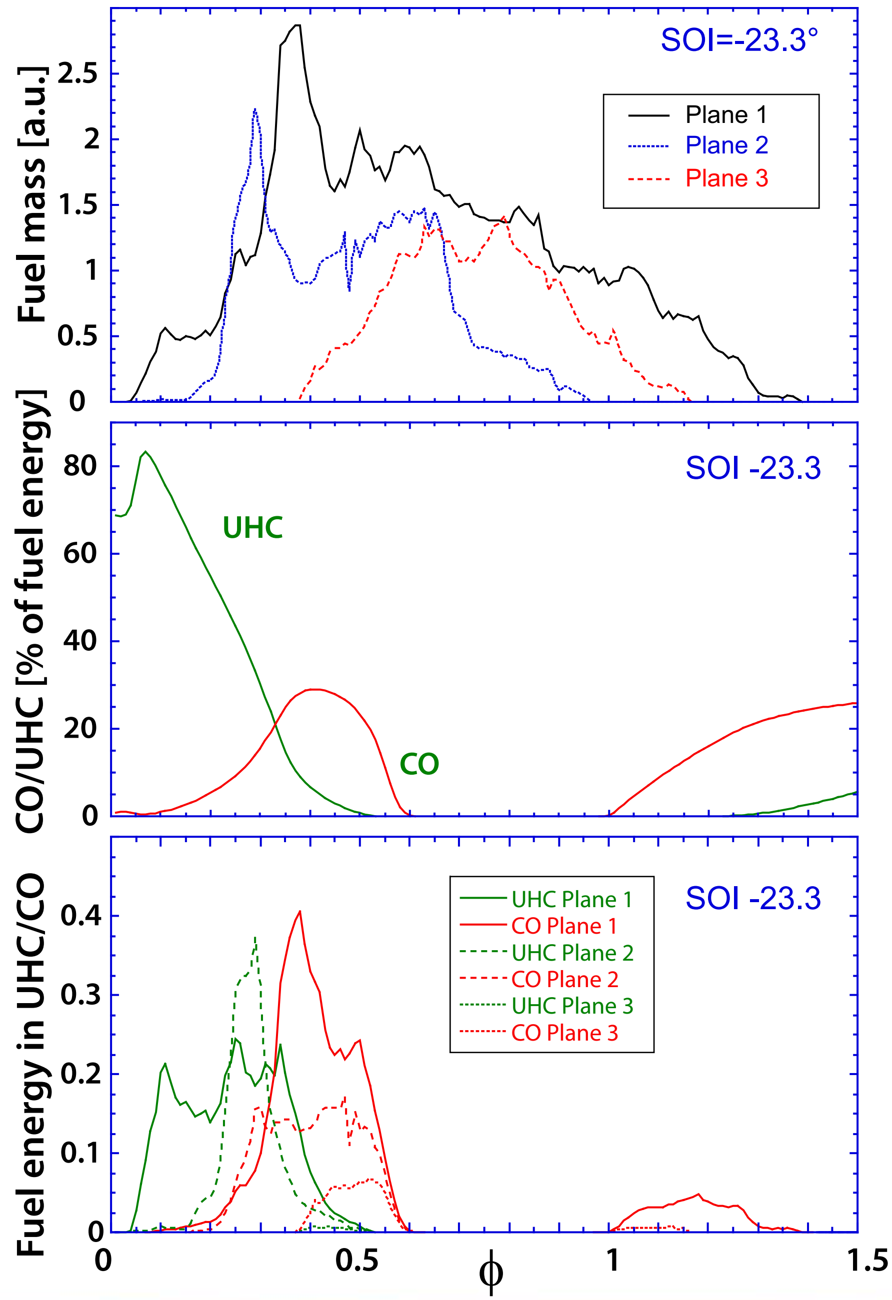


The measured ϕ distributions at CA10 can be linked to the simulations to estimate emissions

- The fuel mass at each ϕ can be computed from the images

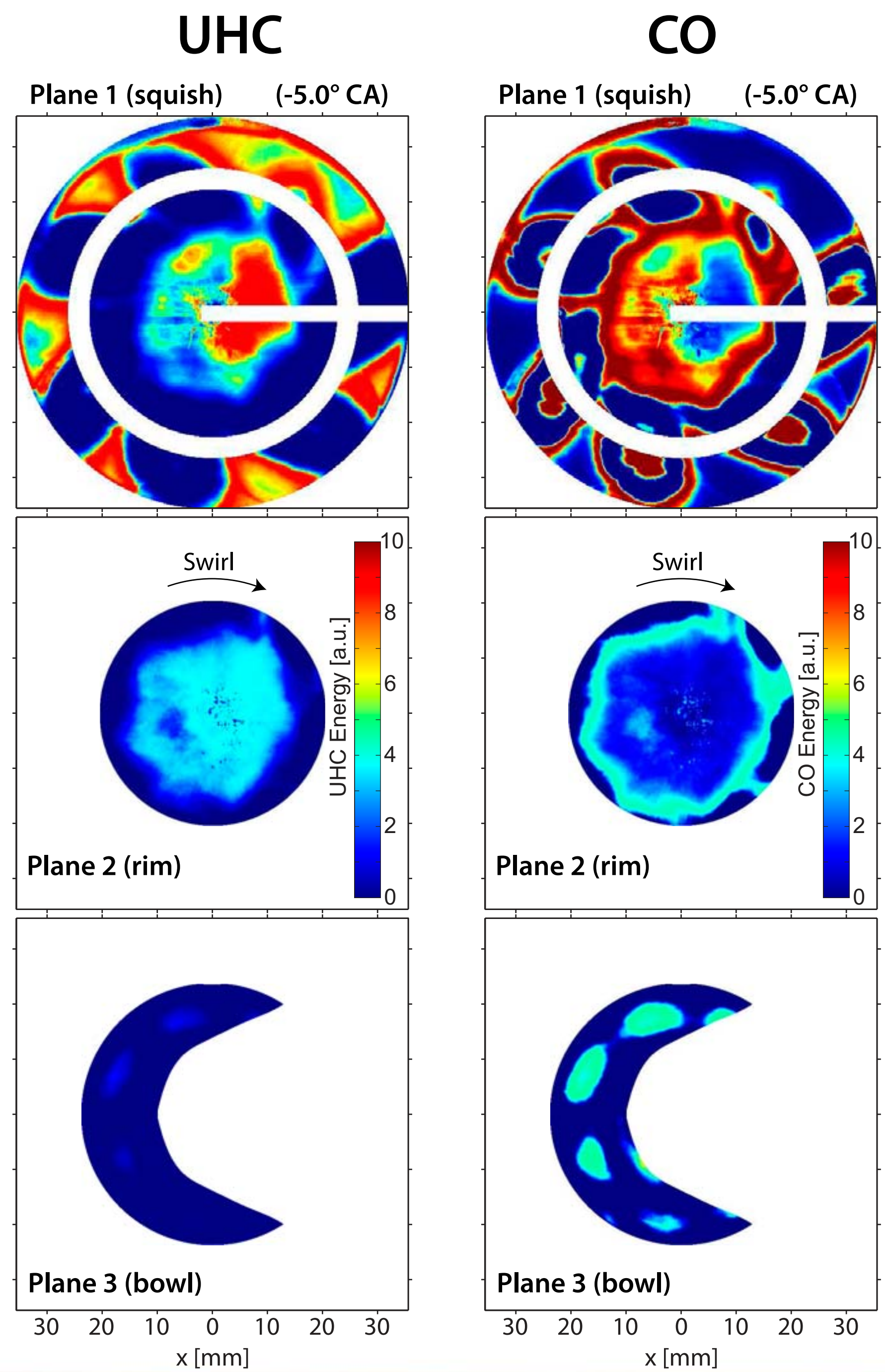
$$m_{fuel}(\phi) = \sum_{j}^{N_j}\sum_{i}^{N_i} m_{fuel,i,j}(\phi) = \sum_{j}^{N_j}\sum_{i}^{N_i} \phi_{i,j} m_{\mathrm{charge},i,j}\left(\frac{m_{fuel}}{m_{\mathrm{charge}}}\right)_{stoich}$$

- Multiplied by the UHC or CO yield predicted in the absence of further mixing
- To provide a qualitative prediction of UHC and CO emissions from both rich and lean sources



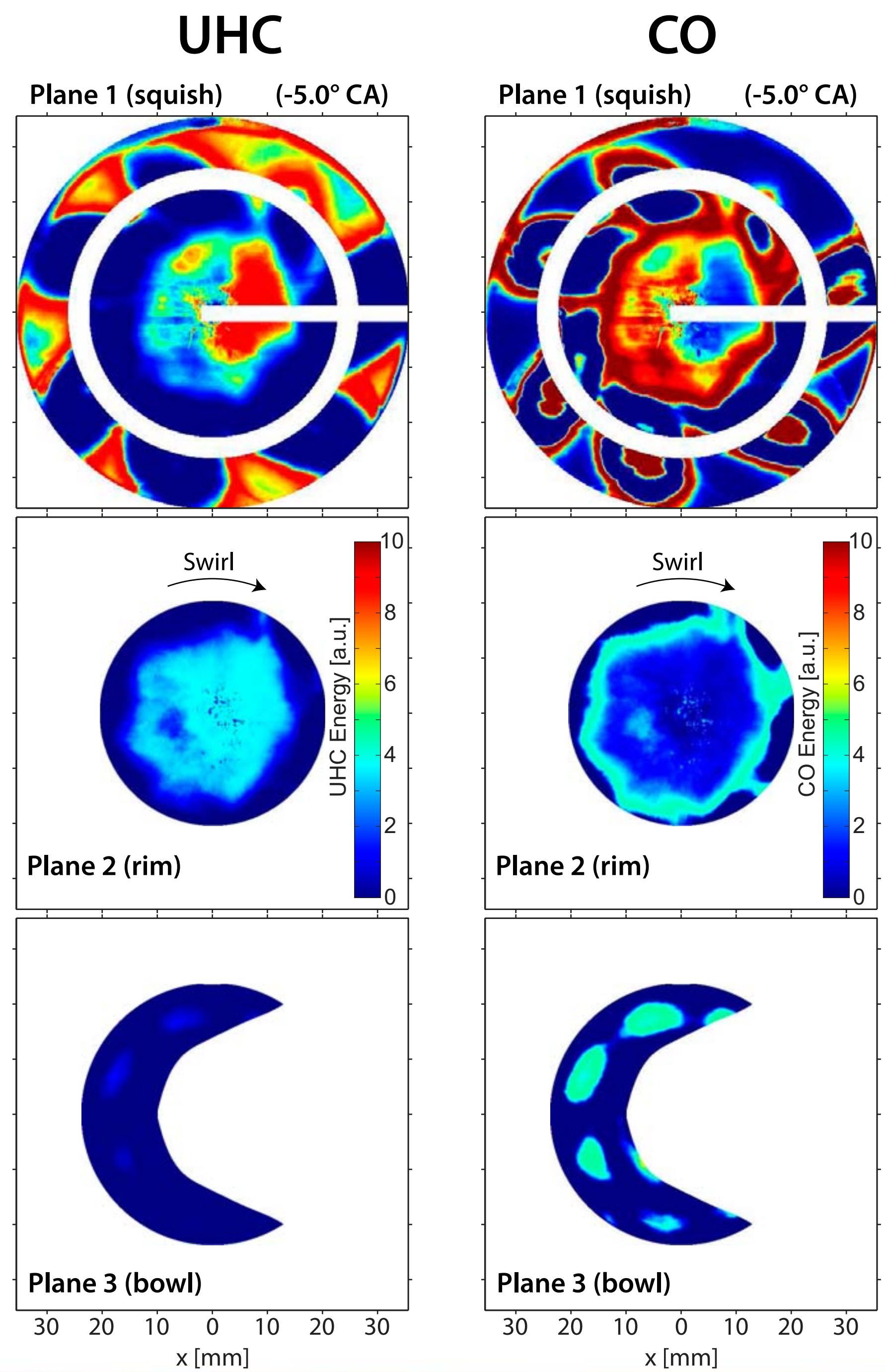
We can also generate images of expected UHC & CO distributions

- Strong bias toward UHC & CO sources from lean mixture in the upper cylinder
- Emissions are expected to be dominated by the squish volume and the upper-central region of the cylinder (as expected from UHC/CO measurements)



We can also generate images of expected UHC & CO distributions

- Strong bias toward UHC & CO sources from lean mixture in the upper cylinder
- Emissions are expected to be dominated by the squish volume and the upper-central region of the cylinder (as expected from UHC/CO measurements)
- **Strong evidence that CO and UHC emissions are very closely linked to the initial mixture preparation process**



Impact of Injection Pressure (ϕ dist. @ CA10)

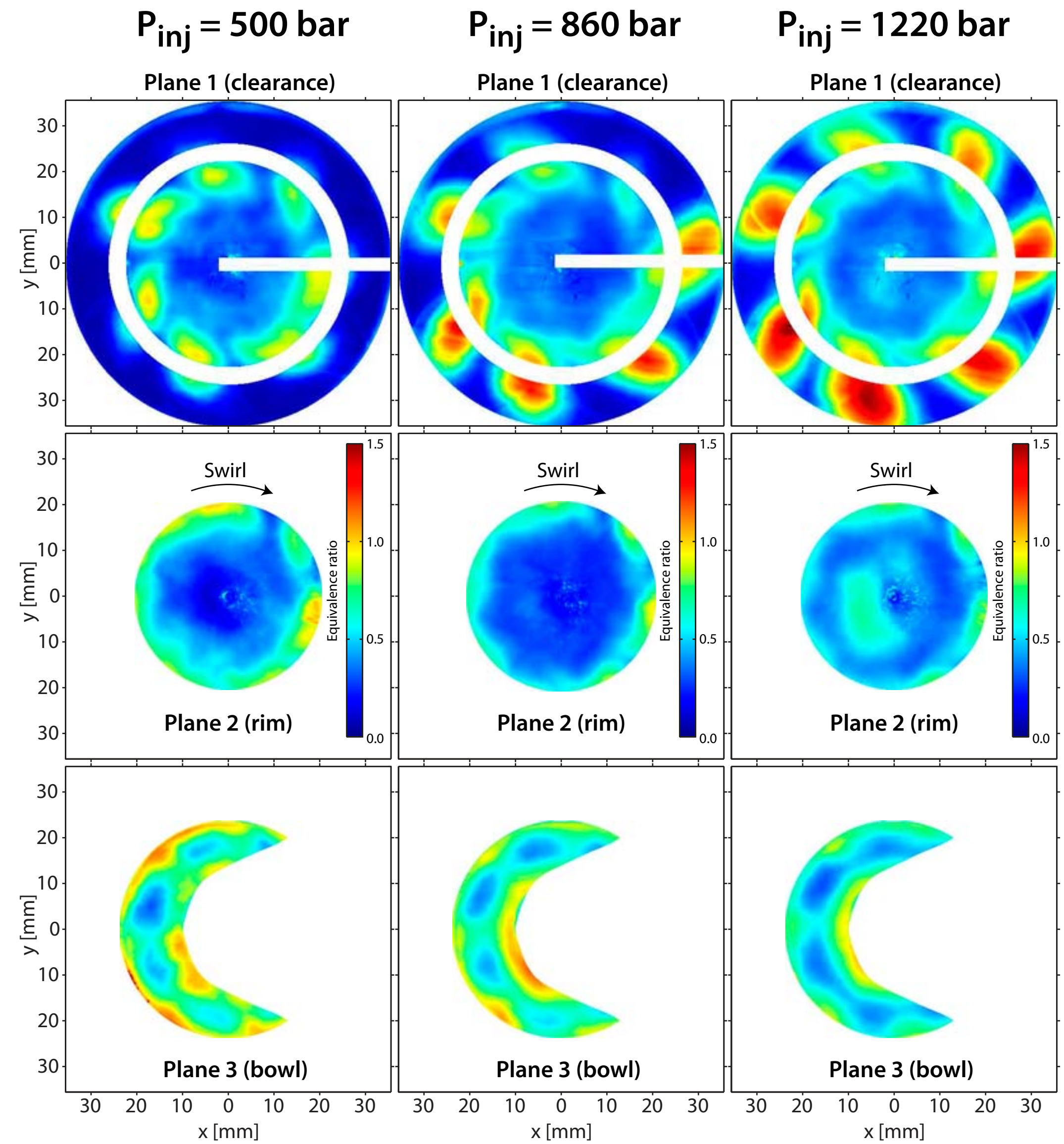
Increased P_{inj} gives:

- Greater penetration into the squish volume, with greater potential for crevice UHC
- Higher ϕ in the head of the jet, with greater potential for soot and rich-mixture CO and UHC
- More over lean mixture in the upper-central region of the combustion chamber
- More over lean mixture deep in the bowl

Engine emissions:

P_{inj} [bar]	CO [g/kg-f]	UHC [g/kg-f]
500	96.7	10.5
860	121.2	11.2
1220	130.0	11.0

See ASME ICES2012-81234 for additional details

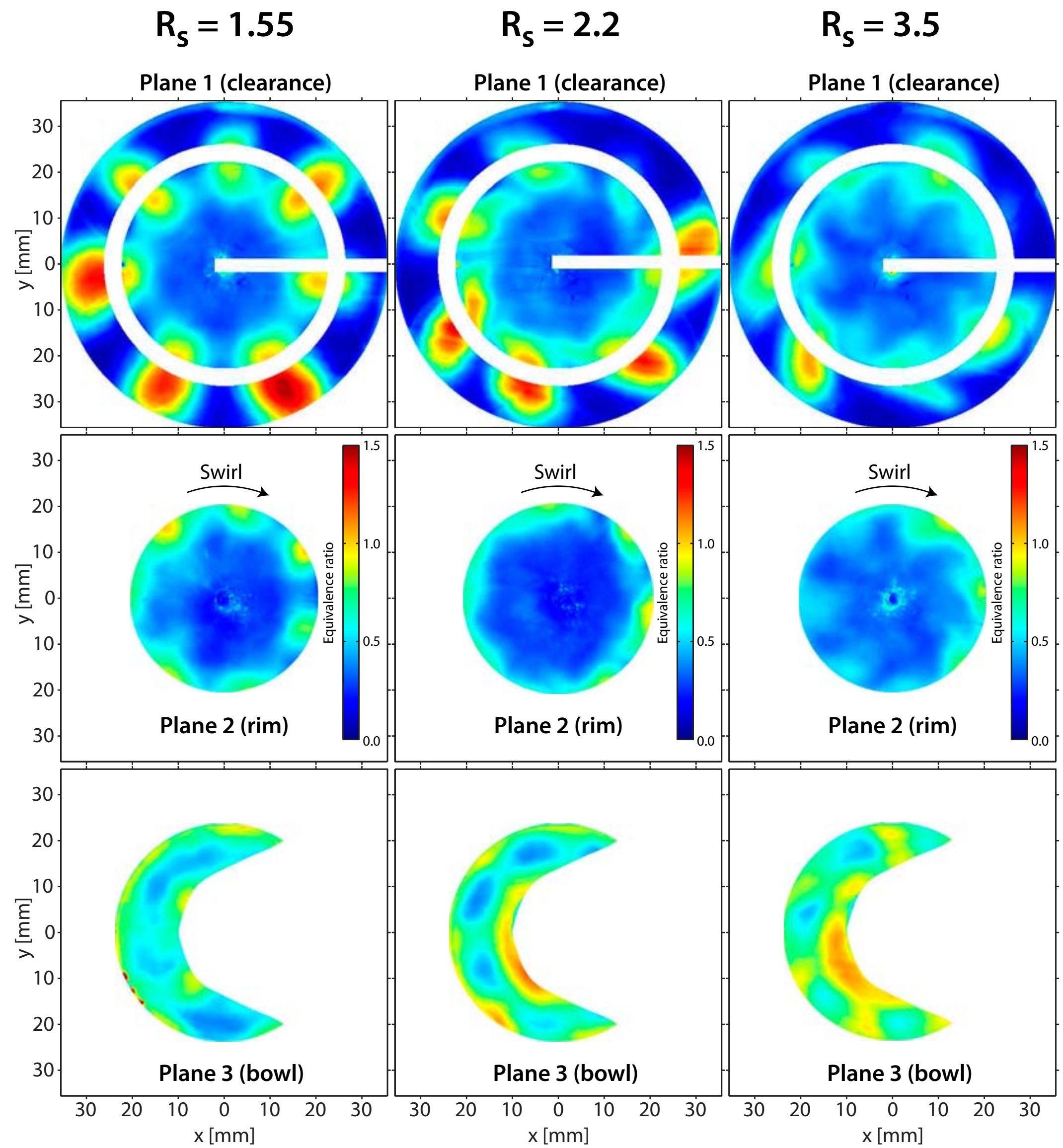


Impact of Swirl Ratio: Start of HTHR (CA10)

Variation of swirl ratio increases some UHC/CO sources and decrease others, resulting in complex emissions behavior

Takeaways:

- UHC and CO sources initially increase with swirl due to increased lean upper cylinder mixture (squish volume)
- CO reduced at higher swirl due to mixture stratification



Engine emissions:

R_s	CO [g/kg-f]	UHC [g/kg-f]
1.55	96.2	8.9
2.2	117.8	10.5
3.5	95.3	12.3

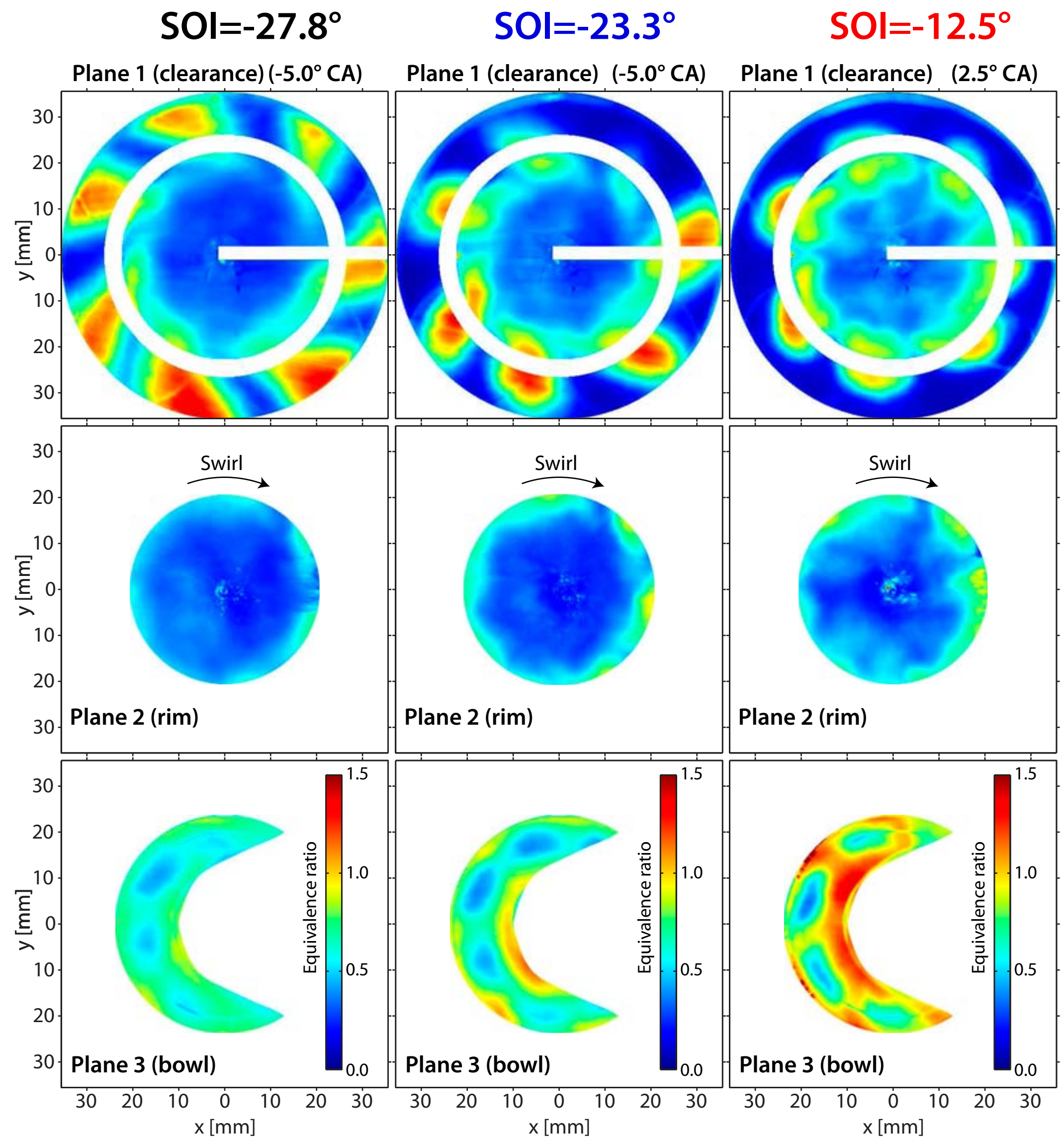
See ASME ICES2012-81234 for additional details

Impact of Injection Timing (Start of HTHR)

Clear trends observed as injection is retarded:

- Less fuel in the squish volume, less penetration, lower peak ϕ
- Less lean mixture between the heads of the jets
- Less over-lean mixture in the upper-central regions
- Richer mixtures deep in the bowl, but not overly rich

From a mixture preparation viewpoint, retarded injection is preferred

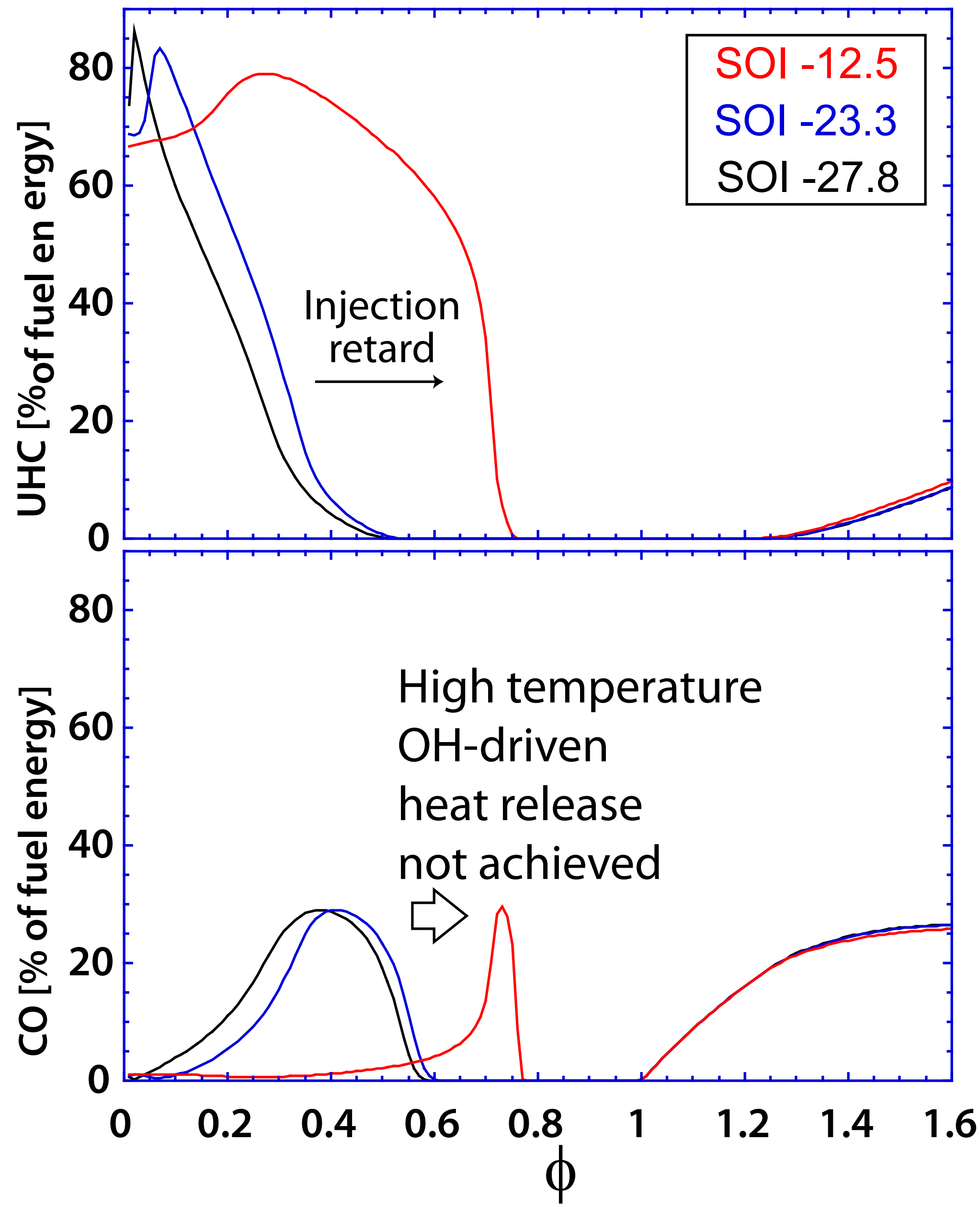


See COMODIA 2012 for additional details

...but retarded injection significantly impedes lean mixture oxidation

- Retarded SOI significantly increases the ϕ at which complete oxidation occurs
- UHC emissions suffer to a greater extent than CO (slow reaction impedes formation of CO)

Optimal SOI timing is due to a balance between mixture formation and kinetics of oxidation



Summary and Conclusions

- Considerable progress has been made in understanding how the mixture preparation process impacts UHC and CO emissions in low-temperature diesel combustion systems

Summary and Conclusions

- Considerable progress has been made in understanding how the mixture preparation process impacts UHC and CO emissions in low-temperature diesel combustion systems
- Emissions expected from examination of the mixture distributions formed during the ignition delay period correlate well with measured engine-out emissions.

The early mixture preparation process exerts a profound influence on the combustion and emissions formation processes

Summary and Conclusions

- Considerable progress has been made in understanding how the mixture preparation process impacts UHC and CO emissions in low-temperature diesel combustion systems
- Emissions expected from examination of the mixture distributions formed during the ignition delay period correlate well with measured engine-out emissions.

  The early mixture preparation process exerts a profound influence on the combustion and emissions formation processes
- Mixture formation and kinetics interact to result in an optimal SOI

  With advanced injection, poor mixture preparation leads to both over-lean and over rich mixture, but fast kinetics promotes oxidation

  With retarded injection, mixture formation is improved, but volume expansion impedes oxidation of a wide range of ϕ

Summary and Conclusions

- Considerable progress has been made in understanding how the mixture preparation process impacts UHC and CO emissions in low-temperature diesel combustion systems
- Emissions expected from examination of the mixture distributions formed during the ignition delay period correlate well with measured engine-out emissions.

  The early mixture preparation process exerts a profound influence on the combustion and emissions formation processes

- Mixture formation and kinetics interact to result in an optimal SOI

  With advanced injection, poor mixture preparation leads to both over-lean and over rich mixture, but fast kinetics promotes oxidation

  With retarded injection, mixture formation is improved, but volume expansion impedes oxidation of a wide range of ϕ

- Our future efforts will be concentrated on multiple injection strategies and on better understanding bowl geometry effects