Low Temperature Automotive Diesel Combustion

Light-Duty Combustion Experiments

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Light-Duty Combustion Modeling

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Program Manager: Gurpreet Singh, DOE EERE-OVT

Project ID # ACE002

Overview

Timeline:

- Project has supported DOE/industry advanced engine development projects since 1997
- Direction and continuation evaluated yearly

Budget:

DOE funded on a year-by-year basis

- SNL $750k (FY12), $730k (FY11)
- UW $230k (FY12), $230k (FY11)

Barriers addressed:

A	Lack of fundamental knowledge
B, G	Lack of cost-effective emission control
C	Lack of modeling capability

Partners:

- 20 industry/national laboratory partners in the Advanced Engine Combustion MOU
- Close collaboration with GM-funded research at UW (Foster)
- Additional post-doc funded by GM

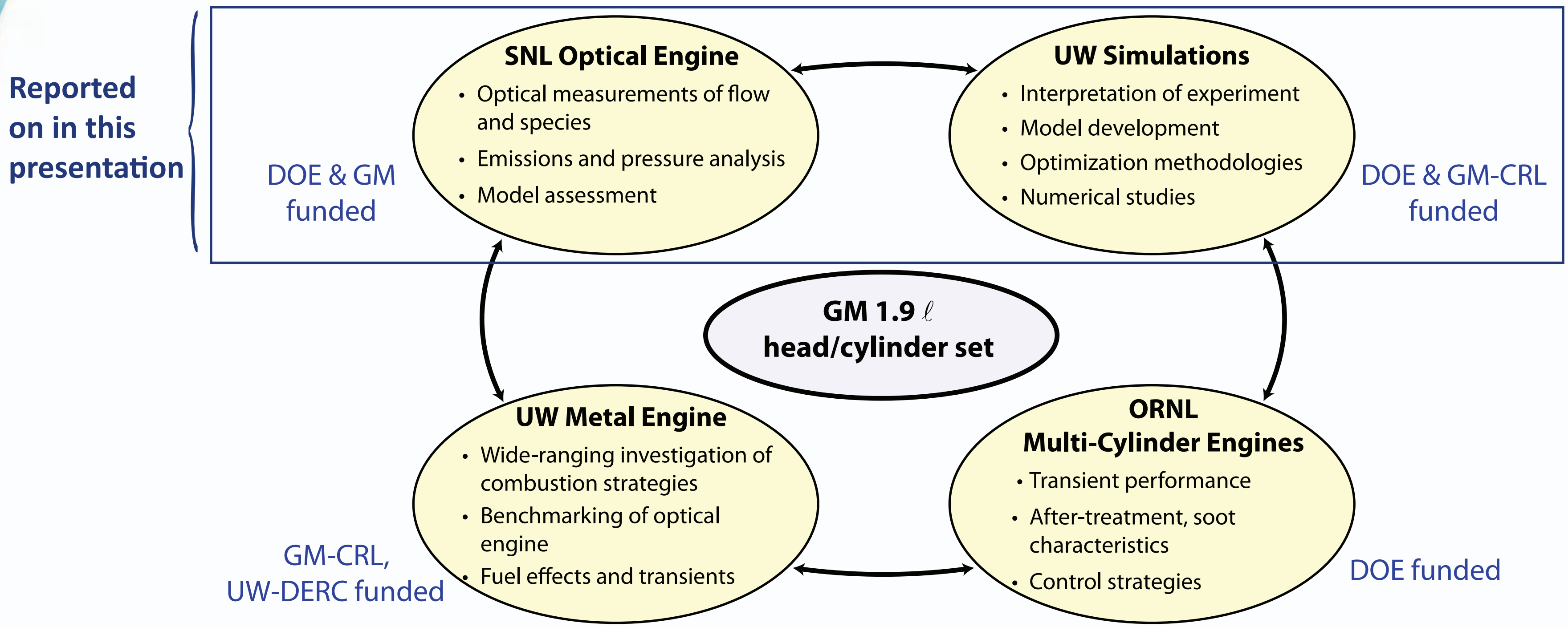
Technical targets addressed:

- 40% diesel fuel economy improvement
- Tier 2, bin 2 emissions
- Emission control efficiency penalty < 1%
- 30 $/kW power specific cost

(Barriers/Targets from EERE-VT 2011-15 Multi-year plan)

Technical/Programmatic Approach

Our approach coordinates and leverages the strengths of several institutions to facilitate development of both fundamental understanding and design tools



Programmatic:
- Multi-institution effort focused on a single hardware platform
- Significant leverage of DOE funds by support from other sources

Technical:
- Closely coordinated program with both modeling and experiments
- Input from and technical transfer to industry inherent in program structure

Collaborations

Within Vehicle Technologies program:

- Formal collaboration between SNL-UW-ORNL
- Data transfer to OEM modelers (e.g. velocity data to Ford)
- Collaboration with heavy-duty/cross-cut projects (ACE001 and ACE005)
- Participation in Advanced Engine Combustion group, including presentations and discussion with 21 industrial/national laboratory partners:

Ex-Vehicle Technologies program:

- Close ties with GM and Ford:
  - GM-funded post-doctoral researcher
  - Monthly teleconferences (Diesel and LES working groups)
- Strong ties to Lund University:
  - Exchange students perform research at Sandia
  - SNL staff participates in LU research projects

Major Technical Accomplishments: Relevance

- Development and application of quantitative, toluene-LIF diagnostic to measure in-cylinder equivalence ratio distributions, and the impact of P_{inj} and R_s on the mixture formation process. Comparison to model predictions. (SNL & UW)

  Barriers/Targets: Improved understanding and improved modeling of in-cylinder processes; Tier 2, bin 2 emissions target; emission control efficiency penalty < 1%

Technical backup slides

- Further quantification of the temperature and composition sensitivity of quantitative in-cylinder CO imaging diagnostic (SNL)

  Barriers/Targets: Improved understanding and improved modeling of in-cylinder processes; Tier 2, bin 2 emissions target

- Low-swirl flow field characterization via PIV and comparison of measured flow fields with revised RNG model predictions (SNL & UW)

  Barriers/Targets: Improved understanding and improved modeling of in-cylinder processes

- Updated conceptual model for light- and heavy-duty LTC combustion based on measured ϕ distributions (SNL)

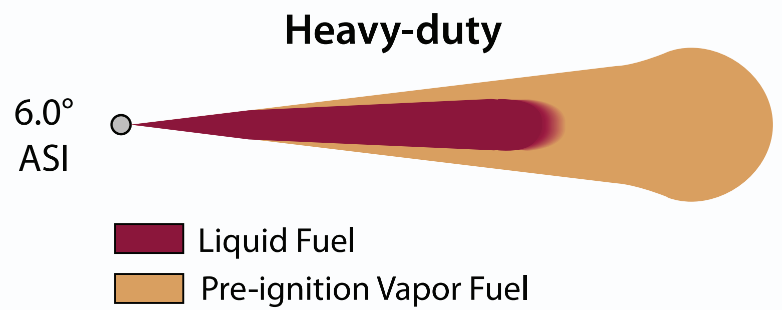
  Barriers/Targets: Improved understanding

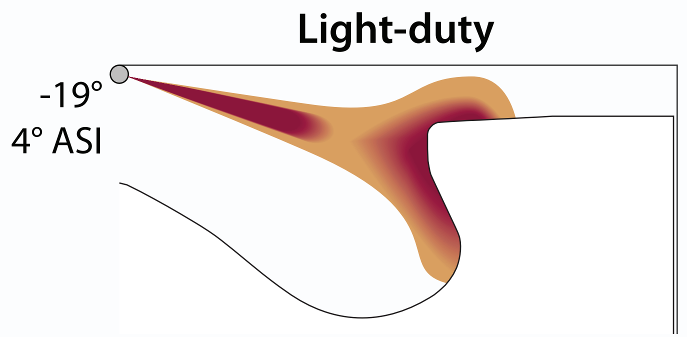
- Soot modeling (UW)

  Barriers/Targets: Improved understanding and improved modeling of in-cylinder processes; Tier 2, bin 2 emissions target

Motivation for Toluene-LIF ϕ Measurements

The initial jet penetration, entrainment and mixture preparation processes in light-duty engines are very different than in the “free-jets” characteristic of heavy-duty engines:





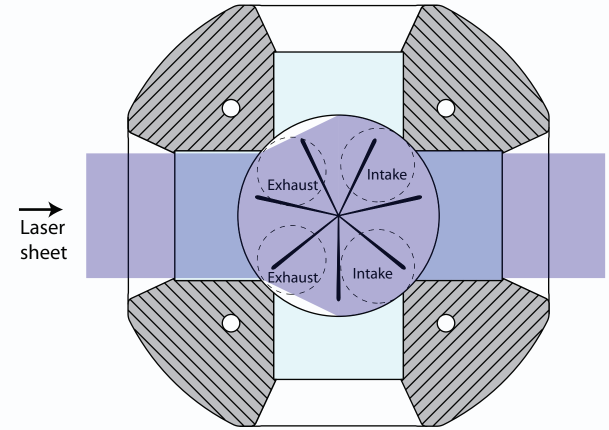
- Light-duty engines have strong wall interactions, including liquid phase impingement and re-direction of jet momentum by the piston surfaces
- Swirl creates a strong cross-flow which, near TDC, is strongest at the jet stagnation region near the bowl lip
- The equivalence ratio distribution at SOC will strongly impact emissions & performance

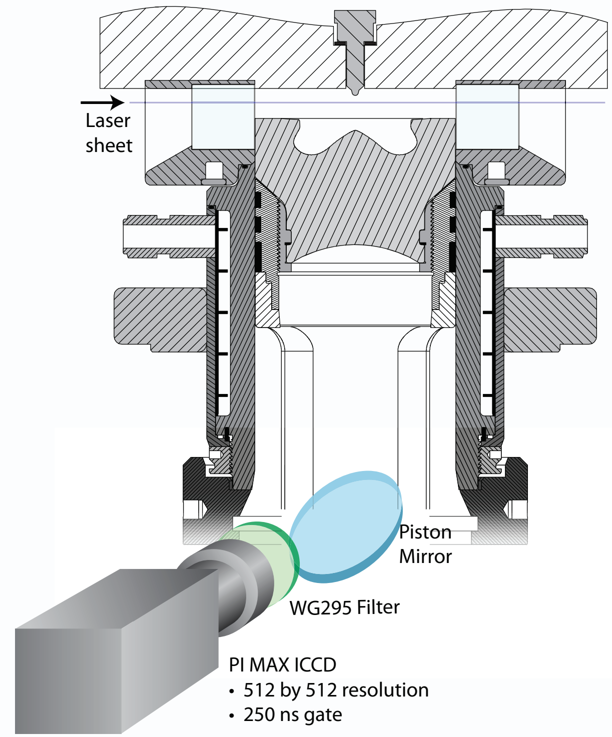
There are no quantitative measurements of the pre-combustion fuel-air equivalence distribution in light-duty engines for CFD validation

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



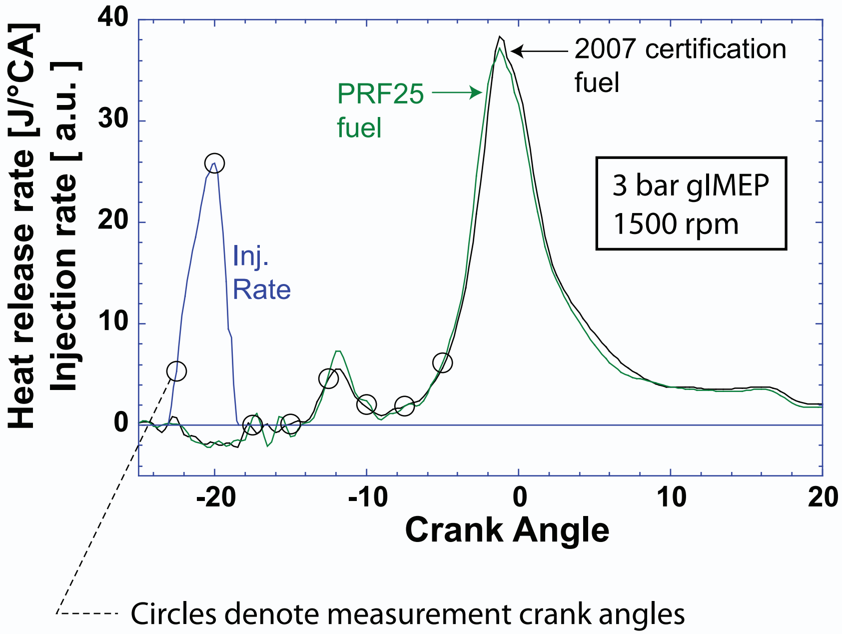


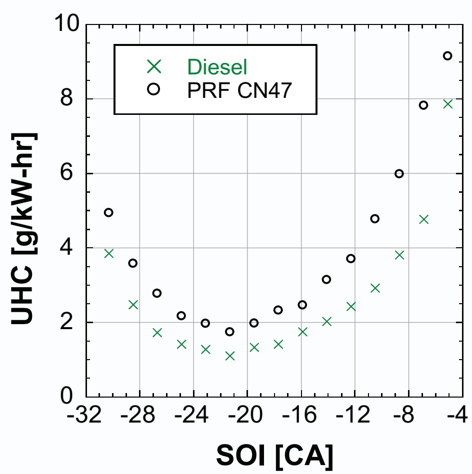
Engine Geometry	
Bore	82.0 mm
Stroke	90.4 mm
Displ. Volume	0.477 L
Geometric CR	16.7
Squish Height	0.88 mm

Injector specifications	
Injector	Bosch CRI2.2
Nozzle Type	Mini Sac (0.23 mm^3)
Holes	7
Nozzle diameter	0.139 mm
Included Angle	149°
Hole geometry	KS1.5/86

Fuel & Tracer Selection / Operating Condition

- Diesel fuel unsuitable due to unknown photophysics
- Toluene tracer (0.5%) in 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





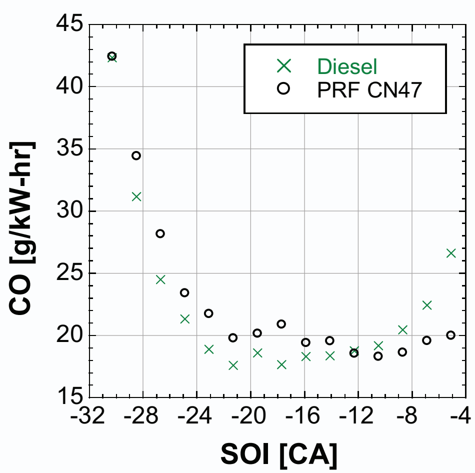
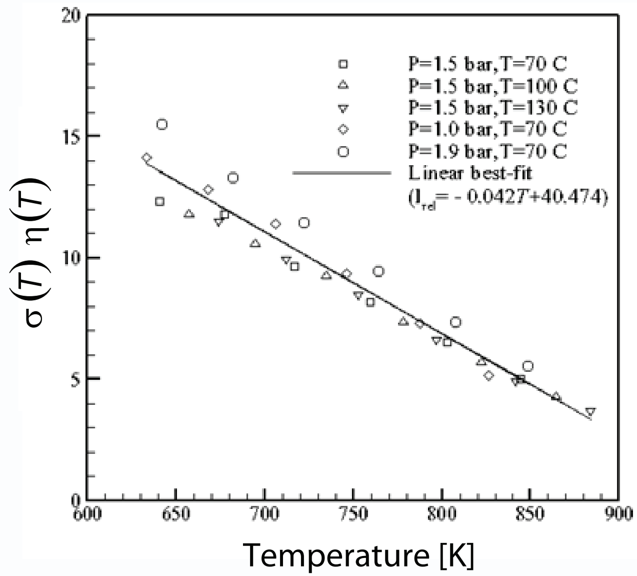


Image Processing Summary

- Background images, obtained with the laser firing but no fuel injection are sub-tracted from the data images
- Images are distortion-corrected, and portions of the image falling in the shadow of the fuel injector or above the reentrant portion of the bowl are masked off
- Calibration images, obtained in a homogeneous fuel-air mixture with a known ϕ are obtained just before the data images
- 100 data and calibration images are acquired at each crank angle
- Local fuel mole fraction is computed from:

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

- The product $\sigma(T)\eta(T)$ was determined from *in situ* calibration studies
- With the calculated $\chi_{fuel,d}$, a local temperature is estimated using an adiabatic mixing model and the $\chi_{fuel,d}$ estimate is refined until convergence is achieved

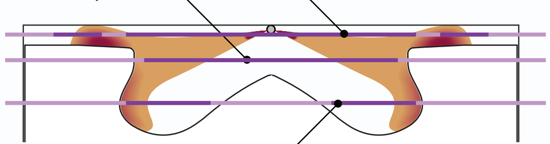


Results: Overview

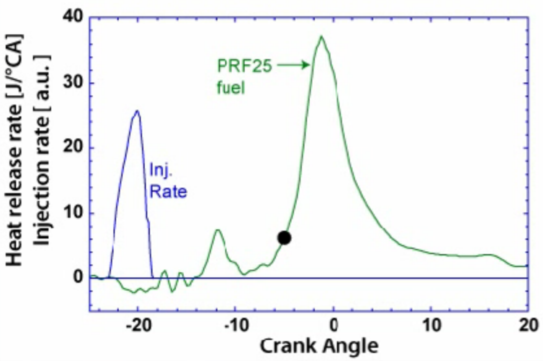
-5.0°CA

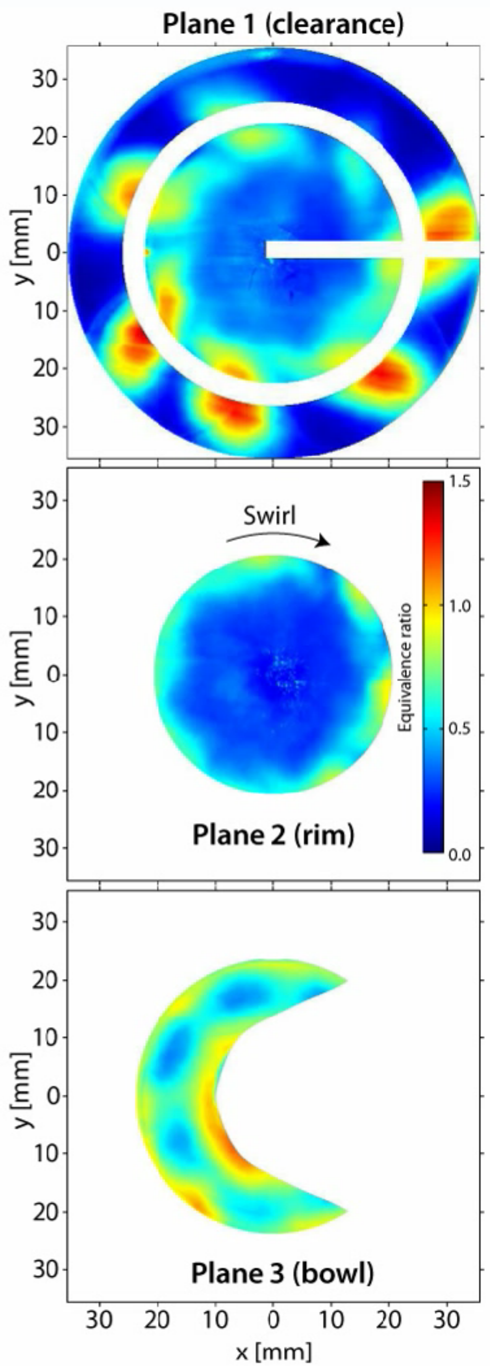
Mixture formation process is clearly illustrated:

- First penetration dominates, then rotation
- Mixing is rapid
  - Reduction of ϕ in jet head
  - Homogenization of upper-central regions
- Significant, repeatable jet-to-jet variation



Darkened areas of the laser sheet indicate visible regions

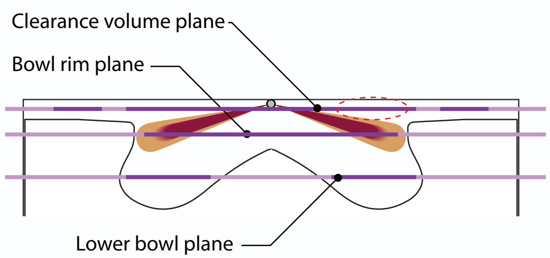




Results: Baseline PCI
P_{inj} = 860 bar, R_s = 2.2
1500 rpm, 3 bar imep

-20.0°CA

- Near the peak rate of injection the jets are just approaching the bowl rim
- Signal within the inner rim plane and bowl is due to LIF from scattered laser light. Brightest regions likely delineate liquid length (correlations give ~ 8.3 mm)
- Large quantities of fuel vapor near the head are unlikely to be associated with diagnostic error (LIF from scattered laser light)



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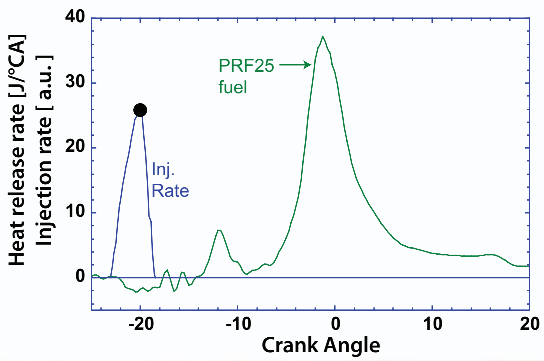
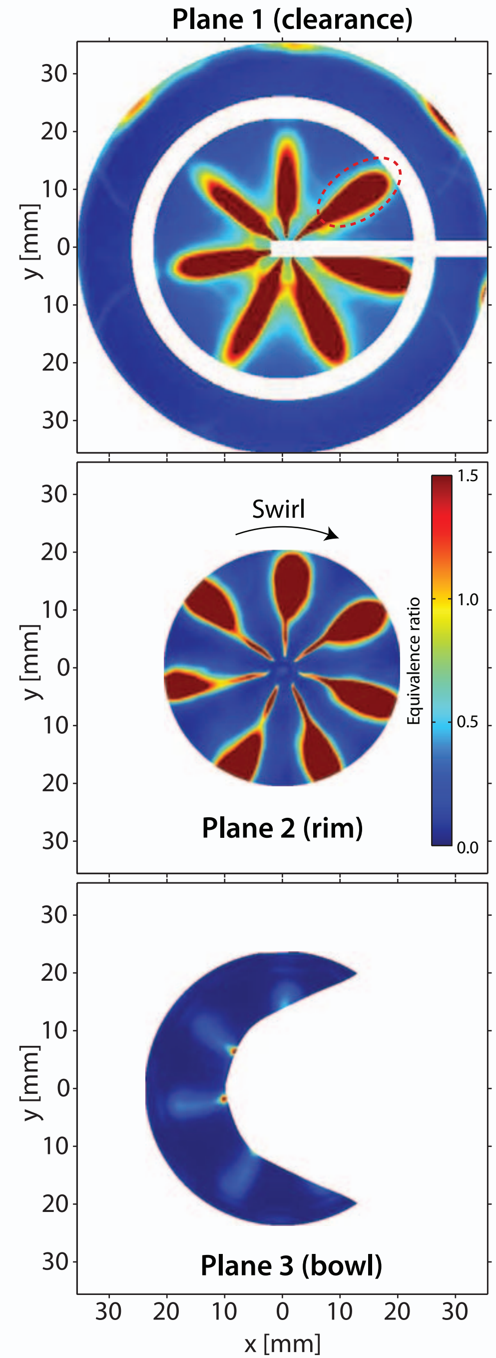


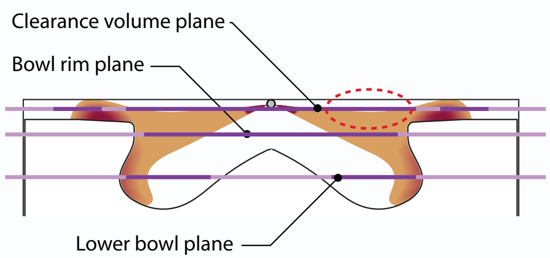


Results: Baseline PCI
P_{inj} = 860 bar, R_s = 2.2
1500 rpm, 3 bar imep

-17.5°CA

- Shortly after EOI, jets have penetrated into the squish volume and deep into the bowl
- Rich mixture dominates, with steep fuel concentration gradients at the head and edges of the jet
  (Consistent with Dec's heavy-duty model)
- Large quantities of fuel vapor near the head and above the piston bowl

  Is this evidence of the Coanda effect?



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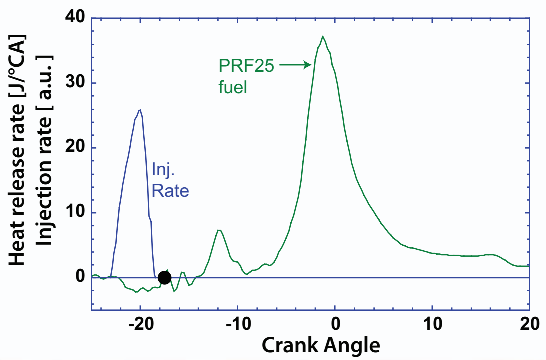
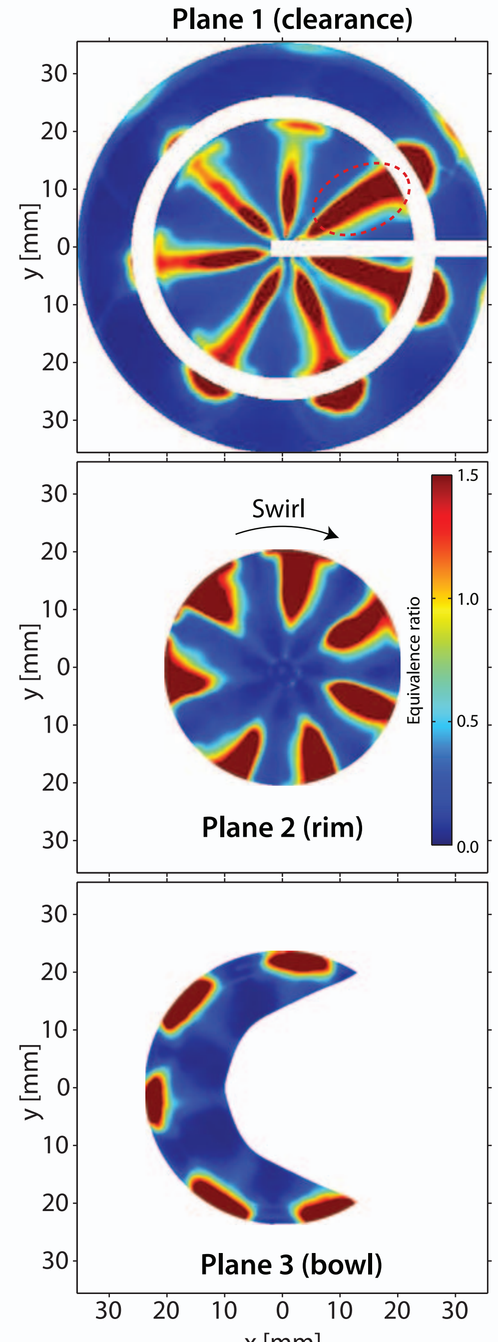
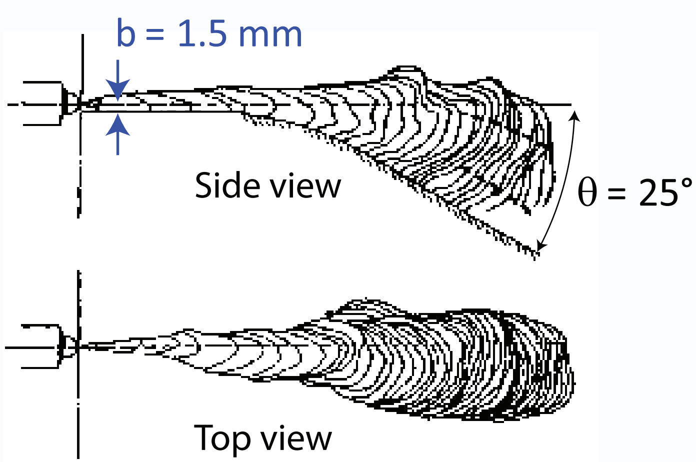




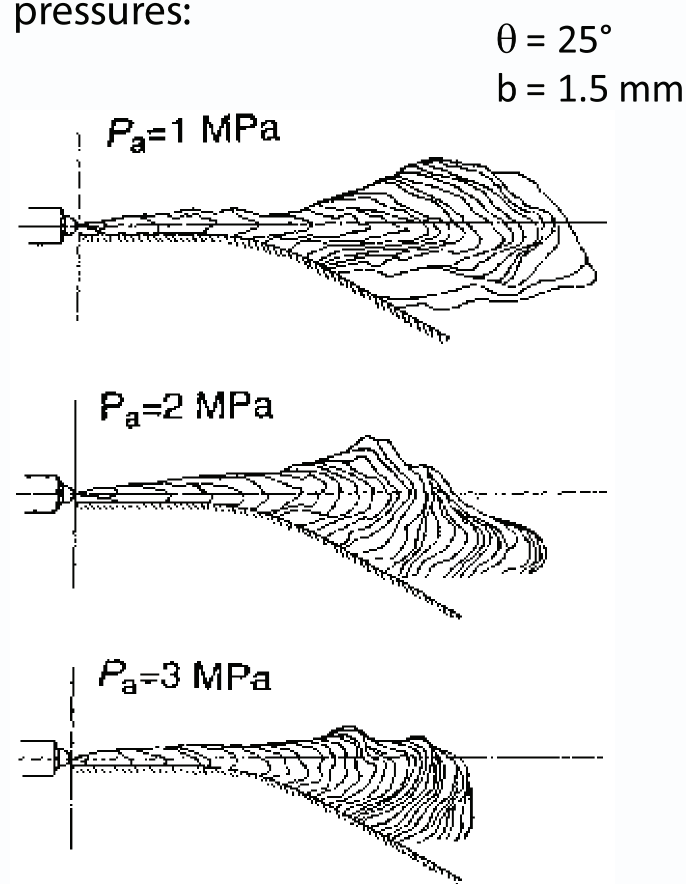
The Coanda Effect

- Pronounced spray asymmetry is introduced by a close-by wall
- The effect has been measured under diesel-like spray and ambient conditions (SAE 951923)
- Capturing this effect in simulations may be essential to predicting fuel distributions near the head

d_{hole}= 0.25 mm
P_{inj}= ~ 200 bar



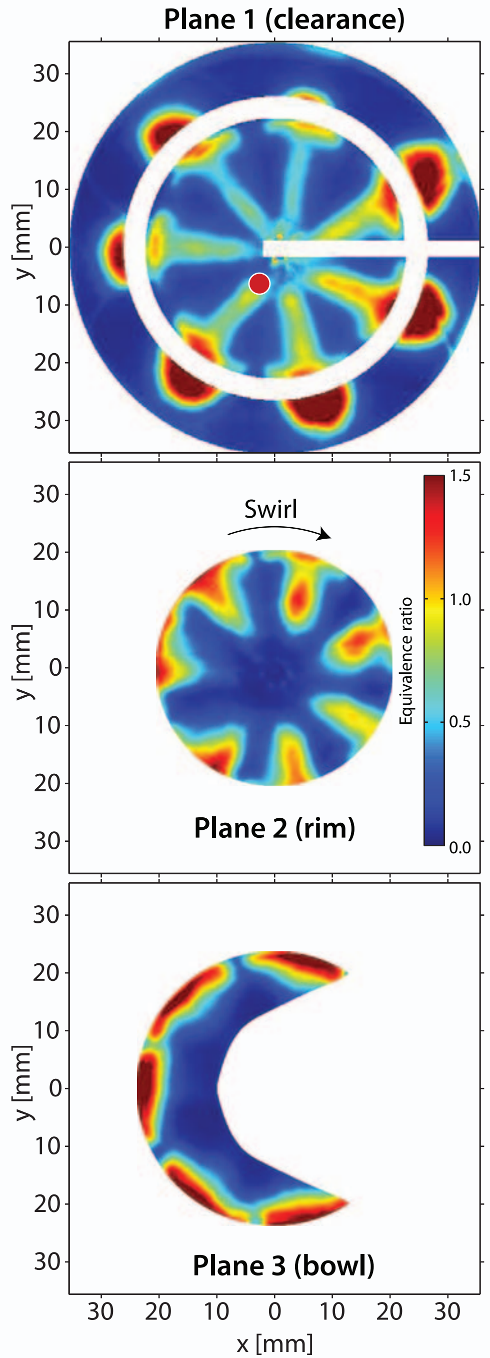
Spray asymmetries are more pronounced at higher ambient pressures:

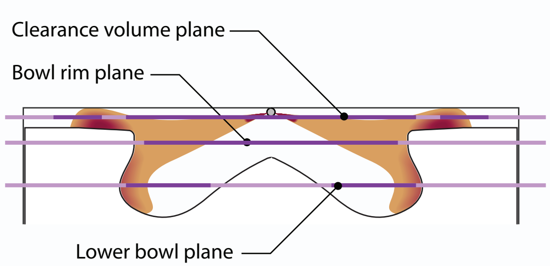


Results: Baseline PCI
P_{inj} = 860 bar, R_s = 2.2
1500 rpm, 3 bar imep

-15.0°CA

- Penetration into the squish volume continues despite opposing squish flow
- Peak ϕ and fuel concentration gradients at the head and edges of the jet are decreasing. Mixture in tails of jets is rapidly becoming leaner
  (Consistent with Musculus's EOI over-leaning work)
- Jet-to-jet asymmetries correlate with swirl offset ●
- Considerable azimuthal spreading, but little radial diffusion, is seen within the bowl





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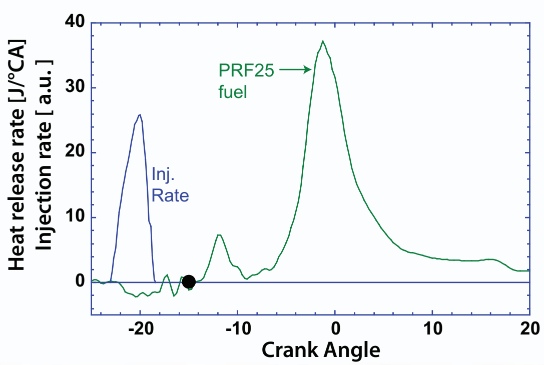
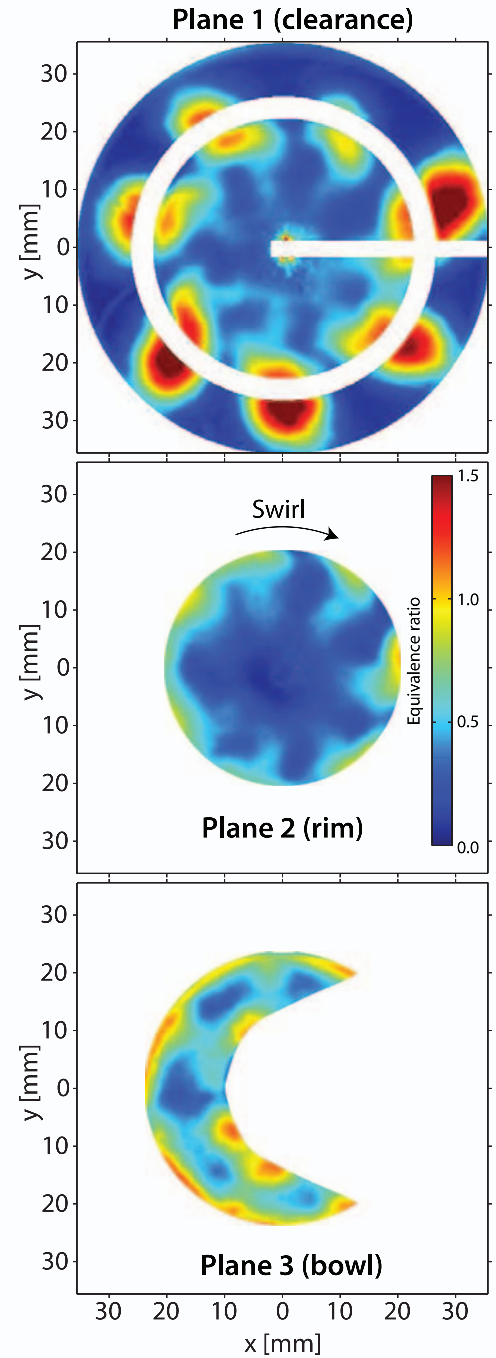
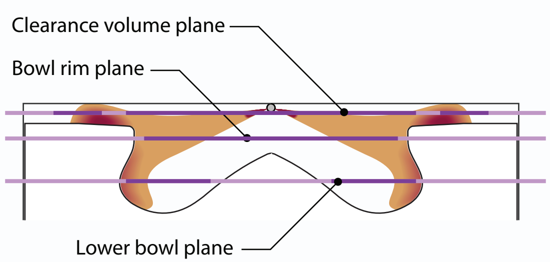


Results: Baseline PCI
P_{inj} = 860 bar, R_s = 2.2
1500 rpm, 3 bar imep

-10.0°CA

- Squish volume penetration continues, peak ϕ and ϕ gradients continue to decrease
- Mixture in tails of jets in clearance plane and bowl rim plane too lean for complete combustion
- Within the clearance plane, the flow in the bowl is rotating faster than within the squish volume
- Jets have traversed the bowl floor and are rising against the bowl pip; radial diffusion within the bowl remains surprisingly small,





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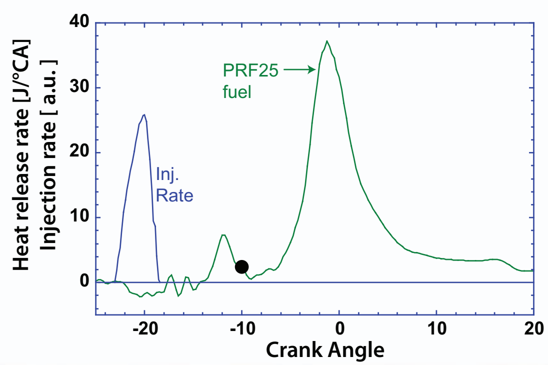
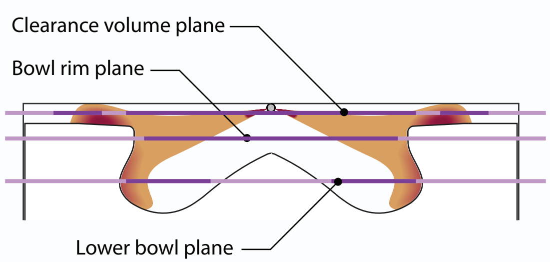


Results: Baseline PCI
P_{inj} = 860 bar, R_s = 2.2
1500 rpm, 3 bar imep

-5.0°CA

At the start of HTHR:

- Fuel in Plane 1 is likely contacting the cylinder walls and will be forced into the ring-land by volume expansion due to 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. This mixture will be forced/drawn into the squish volume by gas expansion and the reverse-squish flow, where we observe UHC and CO during expansion (More analysis in SAE 2012-01-0692)



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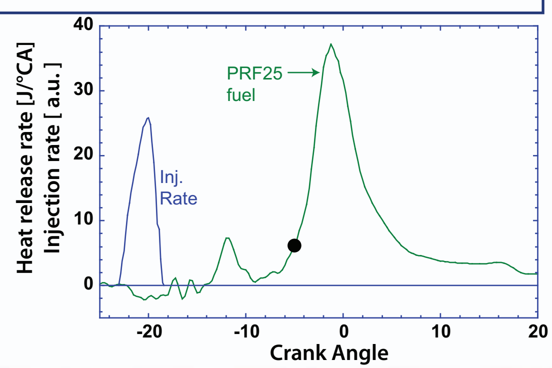
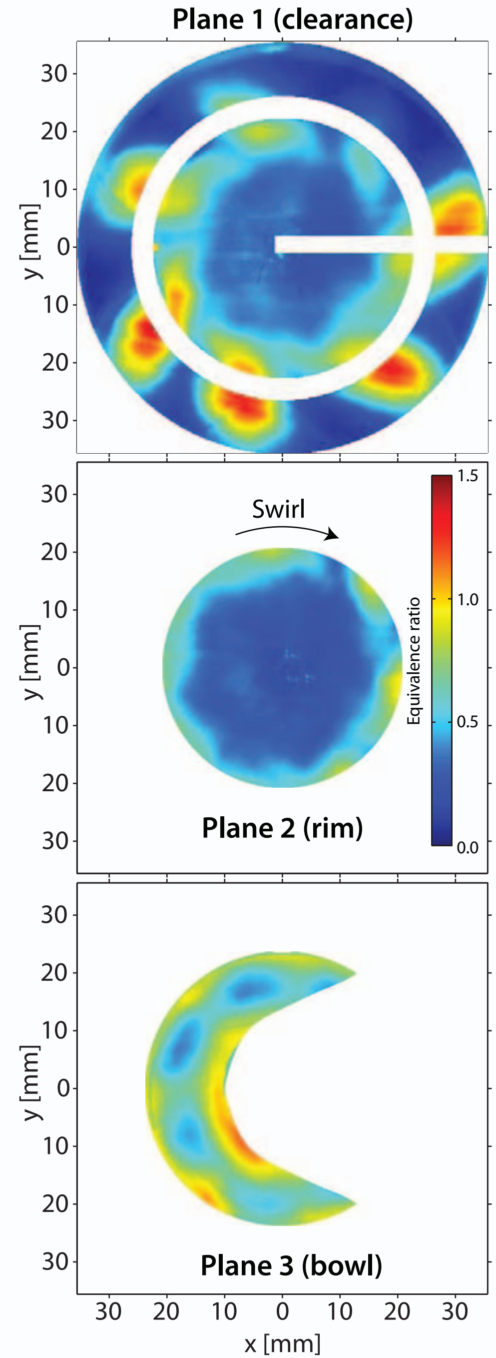


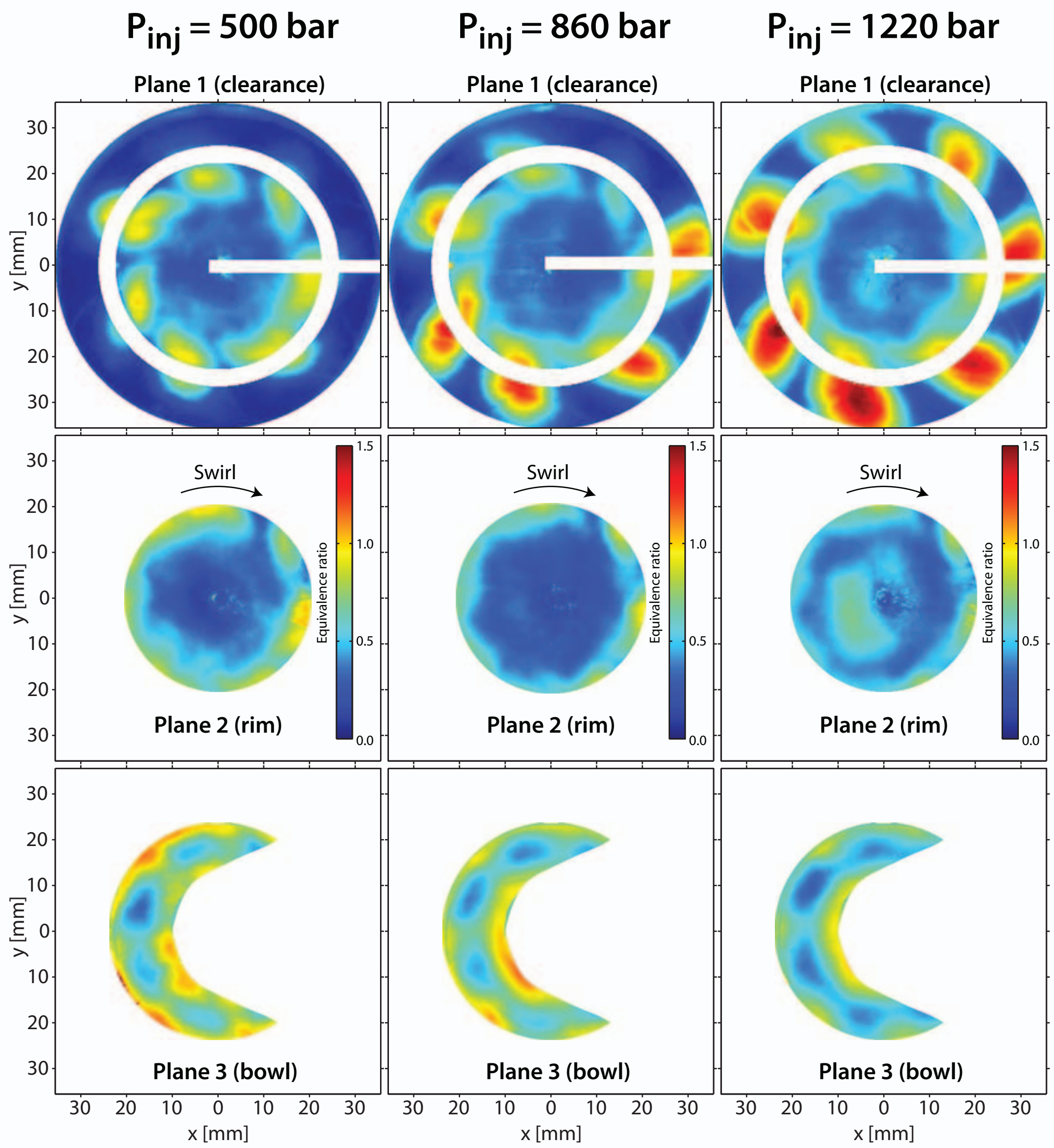


Impact of Injection Pressure: Start of HTHR (-5°)

Increased injection pressure 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

Comparisons with simulations in progress



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

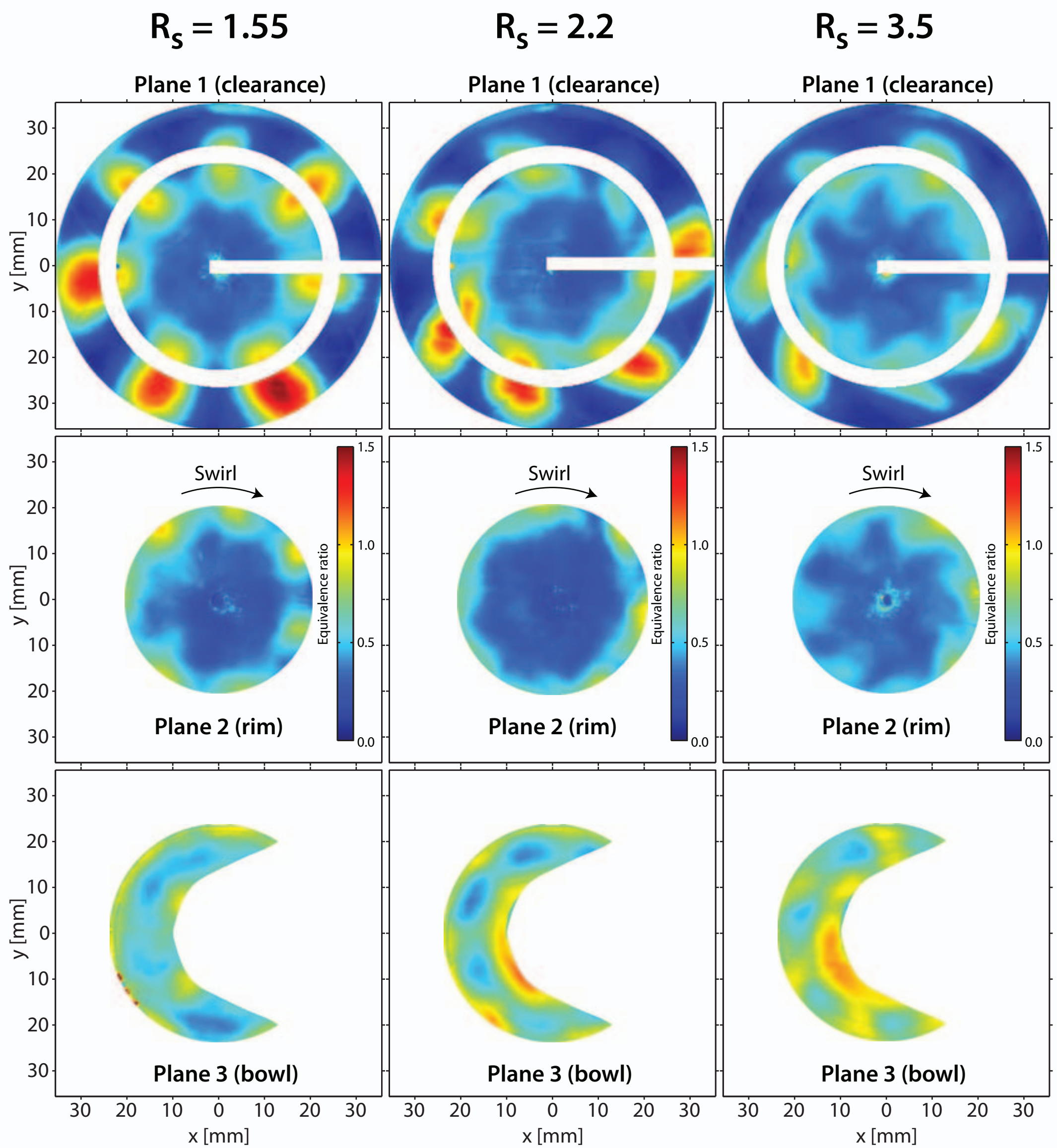
Impact of Swirl Ratio: Start of HTHR (-5°)

Increased swirl ratio results in:

- Increased mixing in the head of the jet; less jet penetration
- Larger mass of over-lean fuel mixture in the upper-central region of the cylinder (particularly at highest R_s)
- Less over-lean mixture low in the bowl

CO emissions trends can be explained by severe over-mixing

Comparisons with simulations in progress



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

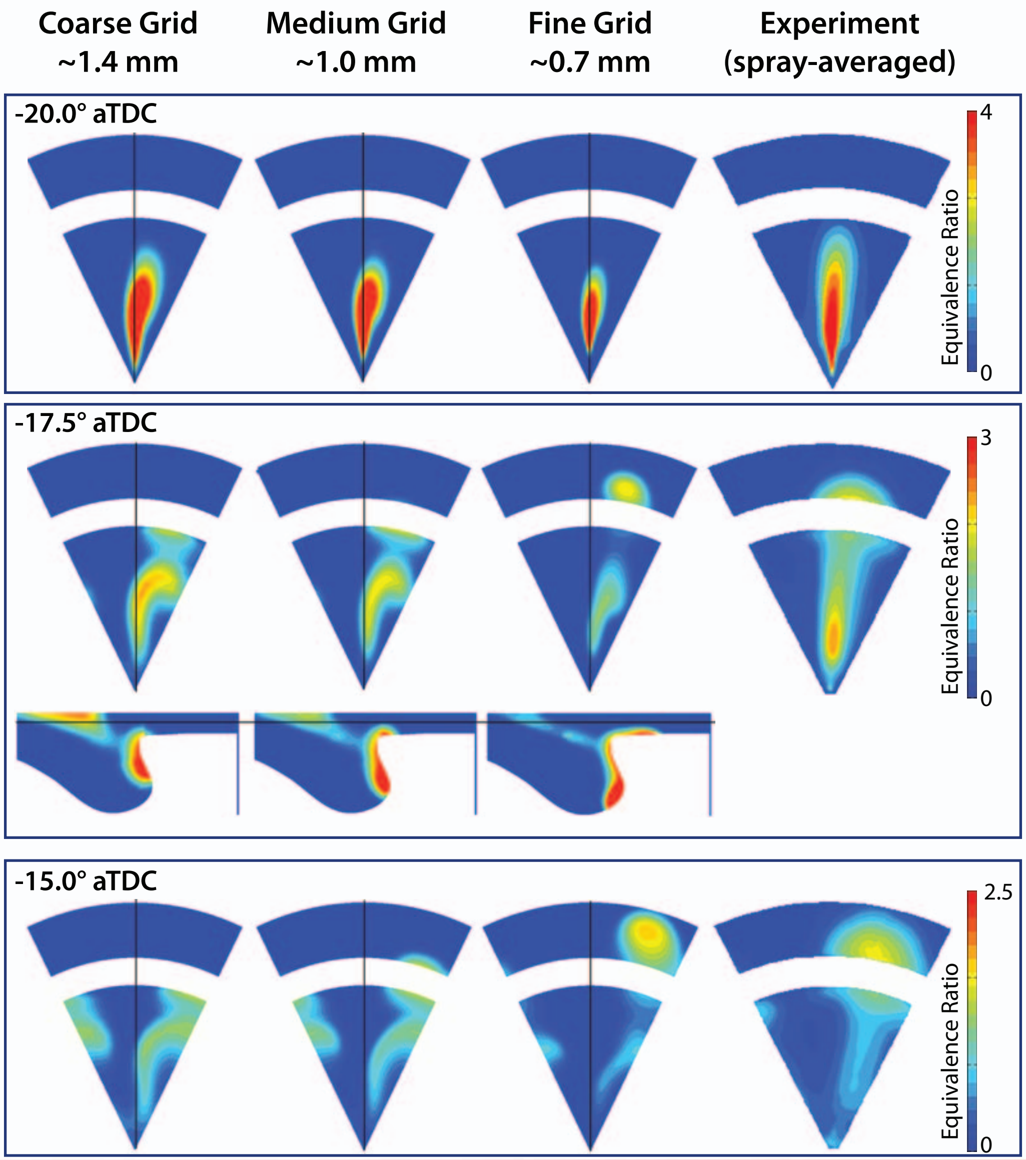
See ASME ICES2012-81234 for additional details

Comparison with Simulations (UW) – *Impact of Grid Resolution*

- Highest resolution is required to capture penetration, but diffusion (mixing) is under-predicted
- The peak equivalence magnitude ratio is well captured
- The impact of swirl on the jet deflection is over-emphasized when the coarser grids are used
- Fuel vapor near the head (Coanda effect) is better captured by the coarser grids

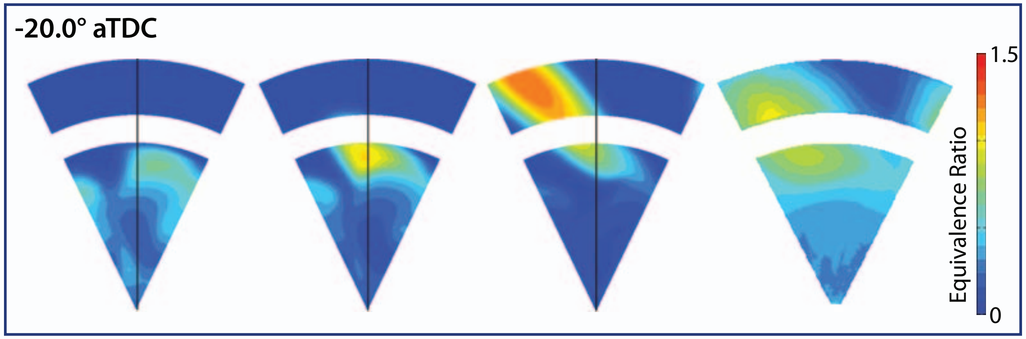
Other factors, such as uncertainty in injection rate profiles, can also influence penetration

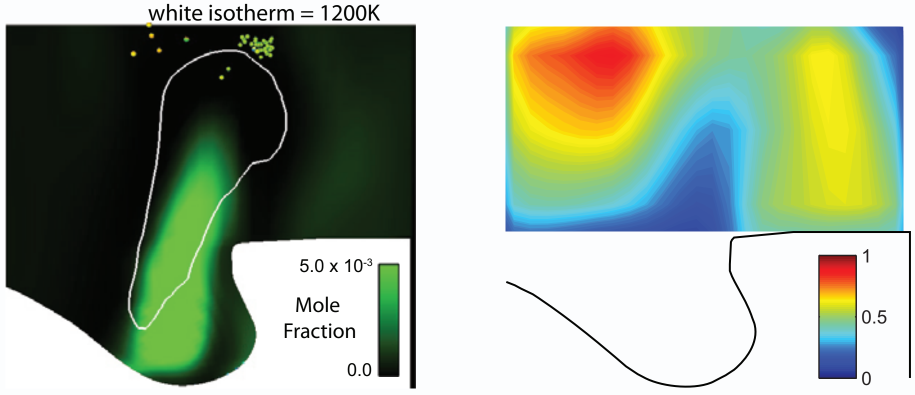
See SAE 2012-01-0143 for additional details



Comparison with Simulations (UW)

- By the start of HTHR, none of the various grids are capturing the peak equivalence ratio, the maximum spray penetration, or the diffusion well





Modeled UHC
(CO is similar)

Measured UHC
(C_2 emissions)

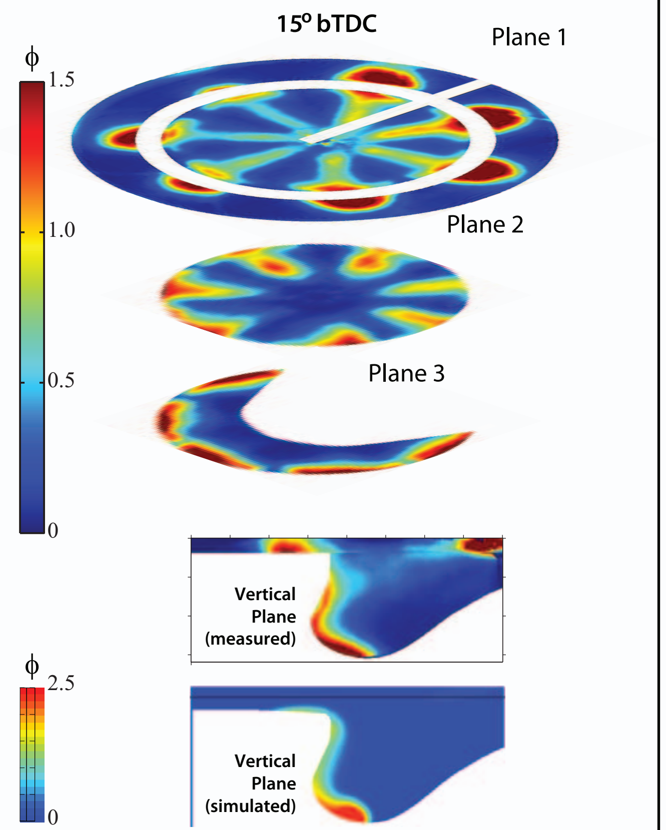
The underprediction of turbulent mixing during the mixture preparation period is fully-consistent with the differences observed between measured and simulated in-cylinder UHC and CO distributions

- Undermixing of main jet (in bowl)
- Squish volume and upper-central UHC

Accurate prediction of mixture preparation is key to accurate emissions predictions

Future Work

- We will continue to focus on the mixture preparation process through measurement and simulation of ϕ-distributions (SNL & UW):
  - SOI Sweeps (in progress)
  - Vertical-plane imaging (on and off-axis)
  - Quantification of measurement accuracy
  - Comparison with simulations for P_{inj} , R_s, and SOI sweeps
- Extend operating condition of mixture preparation to multiple injection strategies (SNL & UW)
  - Post-injection strategies for low-load reduction of UHC and CO
  - Split-injection strategies for noise reduction



Initial vertical plane comparisons are promising

- Continue with model development and refinement (UW)
- Examine impact of asymmetries on combustion and emissions, and our ability to capture them in simulations

Summary

- **Project addresses several barriers/targets identified in the EERE-VT program plan:**
  - Lack of fundamental knowledge
  - Lack of modeling capability
  - Tier 2, Bin 2 emissions
  - 40% diesel fuel economy improvement
  - Emission control efficiency penalty
  - 30$/kW specific cost;
- **Technical accomplishments this reporting period include:**
  - Quantitative measurement and comparison with simulations of in-cylinder ϕ distributions
  - Identification of source of discrepancies between measured and simulated UHC/CO sources
  - Updated conceptual model for light- and heavy-duty LTC combustion
  - Flow field characterization via PIV and comparison to refined generalized-RNG model predictions
  - Improved soot models for conventional diesel and LTC combustion
  - Improved diagnostics for quantitative in-cylinder CO measurements
- **Overall project summary**
  - Since our engine facility upgrade to the GM 1.9 L engine in 2006, we have been building a knowledge base and quantitative measurement data base for model validation that includes measurements of multiple species and flow, all at a consistent set of operating conditions
  - Progress in simulation and modeling includes identification of best practice and tangible improvements in models for soot, vaporization, turbulence, and reduced kinetic mechanisms

Technical Back-Up Slides

Technical backup: CO signal quantification and sensitivity to temperature and composition (SNL)

Task: Quantify potential errors in measured in-cylinder CO concentrations due to unknown composition and temperature within the cylinder

For a quenching dominated signal, the net temperature dependence is given by:

$$N_{CO,B}(T) \propto \frac{f_v \sigma^{(2\nu)}}{T \sum_i \chi_i q_i}$$

Homogeneous reactor simulations have clarified the temperature dependency of the quenching rate:

$$\sum \chi_i q_i * 1.0e\text{-}9\ [\text{bar s}]^{-1} = 8.5629 - 0.0067015*T + 2.0419e\text{-}6*T^2$$

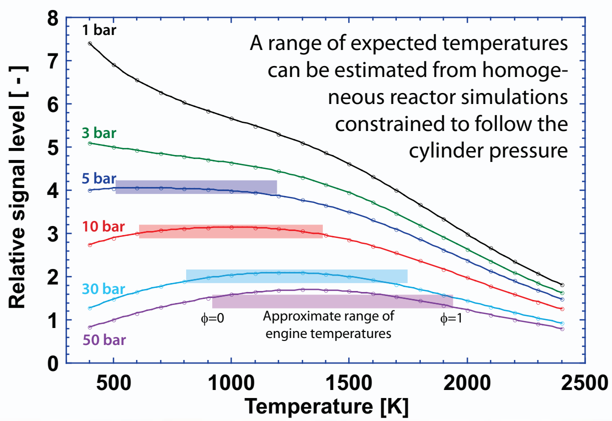
An engineering relation for the T & P dependency of the absorption rate has been obtained from detailed simulation results:

$$f(x,y) * \frac{\sigma_0^{(2)} * G^{(2)}}{2\pi c} = \sigma^{(2)}\ [\text{cm}^4\ \text{s}];$$

x=ln(P), 5 < P < 50 bar
y=ln(T), 500 < T < 1500 K

f(x,y) = P_00 + P_10*x + P_01*y + P_20*x^2 + P_11*x*y + P_02*y^2 + P_30*x^3 + P_21*x^2*y+ P_12*x*y^2

P_00	P_10	P_01	P_20	P_11	P_02	P_30	P_21	P_12
0.977145	-0.465337	-0.165522	0.024578	0.092262	0.005744	-0.00015	-0.0031	-0.004253



The net uncertainty in CO concentration due to temperature uncertainty is very small. At pressures characteristic of the expansion stroke:

30 bar (30°aTDC), $\Delta_{CO} = \pm 6.1\%$
10 bar (50°aTDC), $\Delta_{CO} = \pm 2.7\%$

Technical backup: flow measurement & modeling (SNL & UW)

Task:

Develop & refine the G-RNG k-ε turbulence closure to predict a realistic engine length scale evolution and to provide improved agreement with data

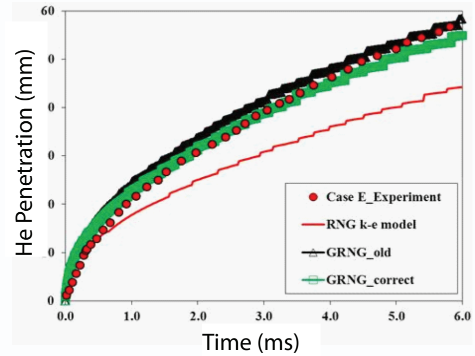
$$\frac{D\varepsilon}{Dt} = C_1 \frac{\mathcal{P}\varepsilon}{k} - C_2 \frac{\varepsilon^2}{k} - \mathcal{R} + (1 - C_3)\,\varepsilon\,(\nabla \cdot \mathbf{U}) + Diffusion$$

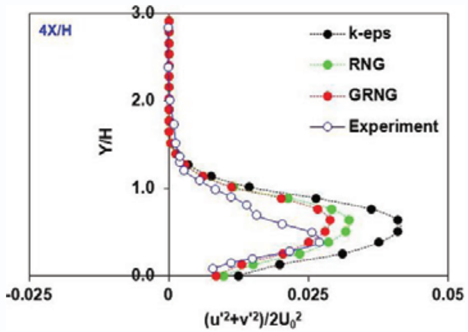
Progress this year:

- Re-evaluated modeling of C_2 based on a constraint relation with the Von Karman constant
- Tested model against compressible jet flows, engine flows during compression, and channel flows

(see SAE 2012-01-0140 for a detailed comparison with engine measurements)

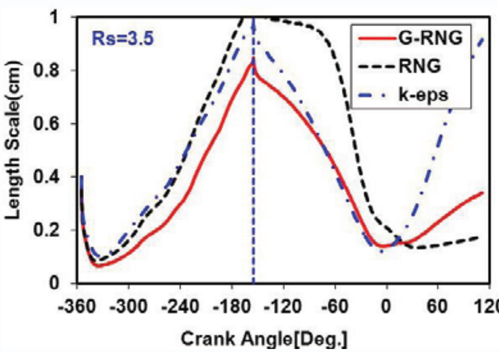
The improved model captures the penetration of a He jet more accurately than the RNG closure or the previous G-RNG model





Turbulence predictions behind a backward facing step are considerably improved over k-ε and the RNG closure

Excessive growth in the modeled length scale during expansion is eliminated



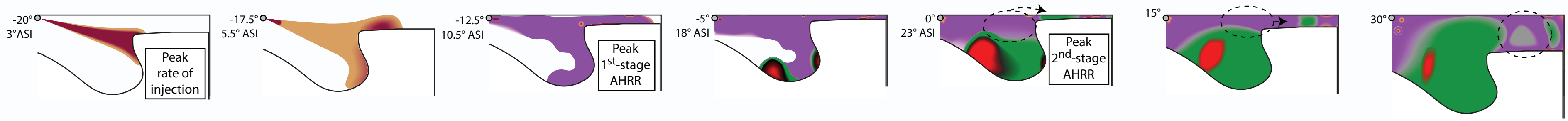
Technical backup: LTC light-duty conceptual model (SNL)

Task:

Revise conceptual model for both early-injection (PCI-like) and late-injection (MK-like) light-duty LTC combustion, incorporating the results of quantitative ϕ imaging

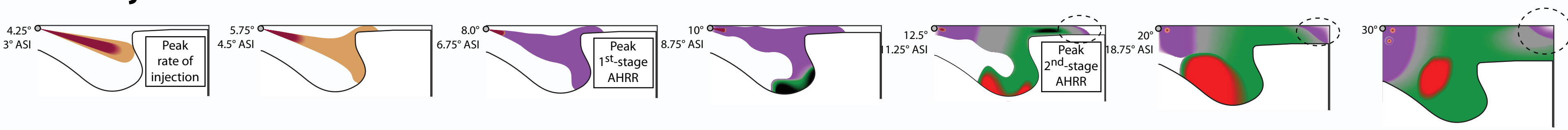
Early injection:

Lean mixture entering squish volume



Late injection:

Lean mixture injected directly into squish volume



- Liquid Fuel
- Pre-ignition Vapor Fuel
- First-Stage Ignition (H_2CO, H_2O_2, CO, UHC)
- Intermediate Ignition (CO, UHC)
- Second-Stage Ignition of Intermediate Stoichiometry or Diffusion Flame (OH)
- Second-Stage Ignition of fuel-rich mixtures
- Soot or Soot Precursors (PAH)

- With early-injection, lean mixtures producing UHC and CO in the squish volume are forced there by gas expansion within the bowl and the reverse squish flow
- With late-injection, lean mixtures in the squish volume come from fuel injected directly into the squish volume, near the head and in regions between the jets

Technical backup: soot modeling (UW)

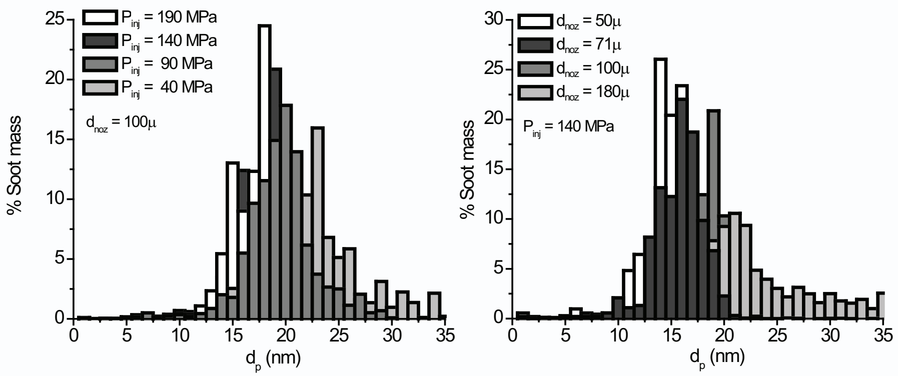
Task:

Develop combustion and soot formation & oxidation models valid for a multi- component fuel, incorporating a vaporization model capable of capturing fuel

Progress this year:

- Examined particle size behavior in heavy-and light-duty engines with single-component fuel
- Coupled model to multi-component vaporization model & tested against single-comp. benchmark
- Incorporated multi-component (PRF) kinetic mechanism
- Incorporated reduced PAH kinetics
- Validated model against engine and flame data

Example results:



Soot particle size tracks expected trends; soot diameter decreases at higher P_{inj} and with smaller nozzle diameter

- The model currently underpredicts the axial locations of peak soot and peak soot concentrations
- Sensitivity studies point to surface growth as a key area for improvement