Light-duty Diesel Combustion Research

Advanced Light-Duty Combustion Experiments

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Light-Duty Combustion Modeling

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This presentation does not contain any proprietary, confidential, or otherwise restricted information

Project ID#:
ace_02_miles

Overview

Timeline

- Project has provided fundamental research supporting DOE/industry advanced engine development projects since 1997
- Directions and continuation evaluated annually

Budget

Fully funded by DOE on a year-by-year basis

- SNL \$670k (FY08), \$680k (FY09)
- UW \$230k (FY08), \$230k (FY09)

Barriers addressed

- Inadequate understanding of the fundamental mixture formation, combustion, and emissions formation processes
- Inadequate predictive simulation capability
- Specific barriers
  - Limited speed/load range for LTC
  - High HC and CO emissions (low eff.)
  - System costs (minimize aftertreatment)

Partners

- 15 industry partners in the Advanced Engine Combustion MOU
- Collaboration with GM-funded CRL at UW (Prof. Foster)
- Additional post-doc funded by GM

Objectives

- Identify the sources of combustion inefficiency (CO and UHC emissions) in low-temperature diesel combustion regimes
- Improve our fundamental understanding of in-cylinder processes, multidimensional models and modeling practice, and measurement techniques and data employed for model validation

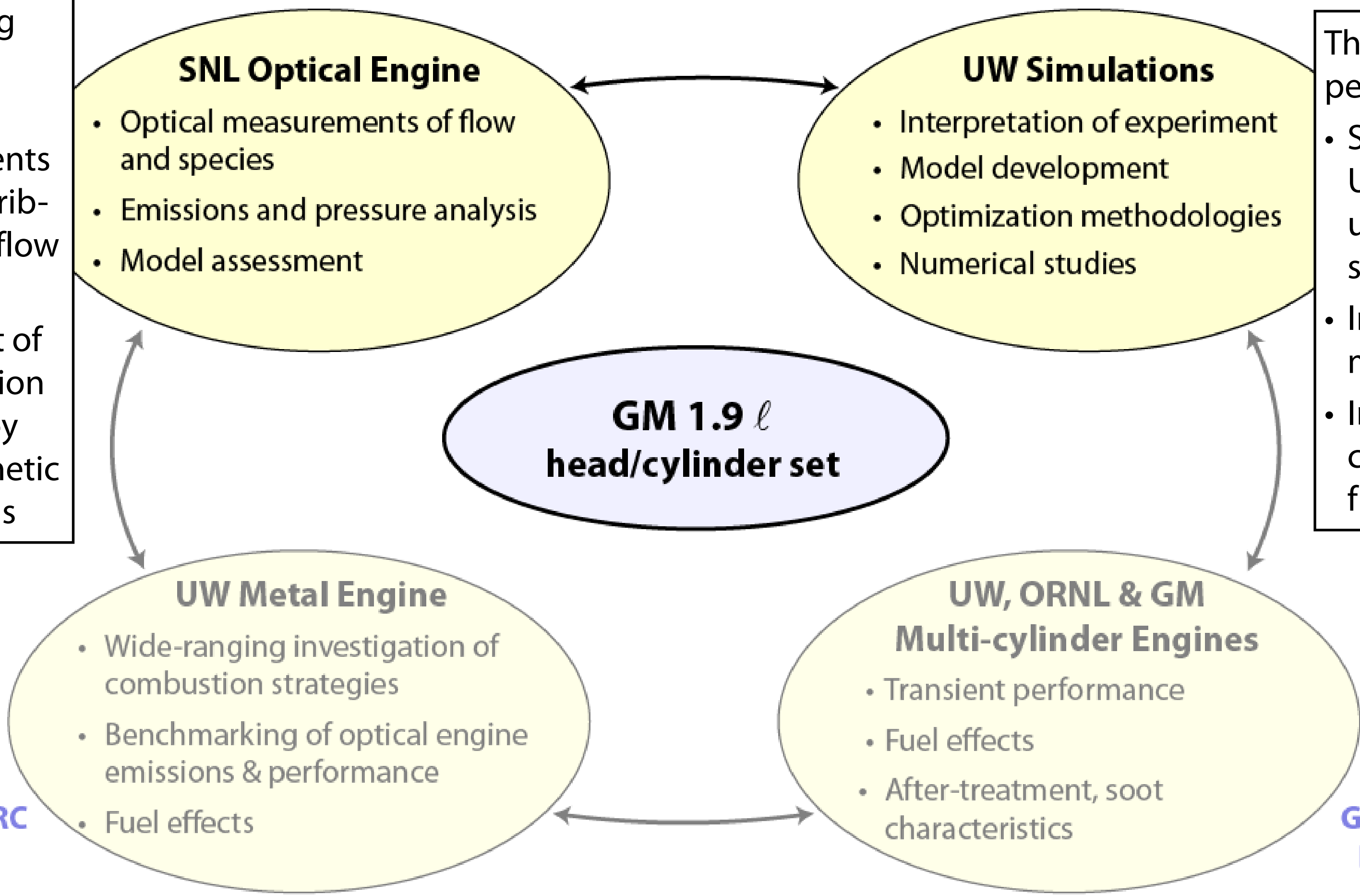
These objectives are met through:

- Development and application of experimental techniques to obtain full-field scalar (UHC, CO) measurements to assess model accuracy and practice
- Careful comparison of model predictions with experimental data
- Feedback and improvement of both the modeling and the experiments

Our approach coordinates and leverages the strengths of several institutions and $$ sources

This reporting period:

- In-cylinder measurements of UHC distrib-utions and flow structures
- Assessment of UHC oxidation predicted by reduced kinetic mechanisms



This reporting period:

- Simulations of UHC distrib-utions and flow structures
- Improved comb. models
- Investigation of crevice driven flows

GM, UW-DERC funded

GM, UW-DERC, DOE funded

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

Overview of technical accomplishments in this reporting period

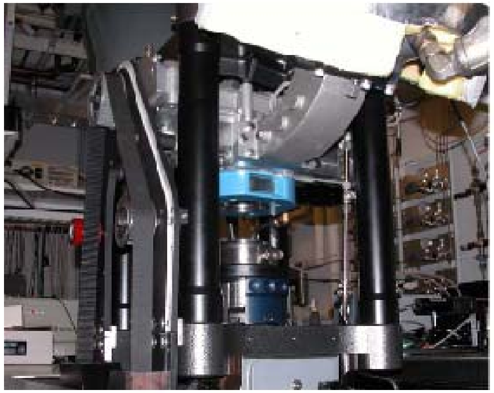
SNL:

- Compared full and reduced kinetic mechanisms in homogeneous reactor simulations, identified short-comings in rich-mixture UHC oxidation behavior
- Developed and applied:
  - Image distortion and flat-field corrections for images obtained in the piston bowl
  - 355 nm PLIF and 1-d, spectrally-resolved imaging diagnostics to investigate UHC
  - PIV and elastic scatter imaging to measure liquid fuel and flow structures
- Employed the above data to examine the UHC distributions and flow structures and to assess model performance and practice
- Applied combined CO and UHC diagnostics to full-factorial experiment designed to investigate the impact of squish height and spray targeting

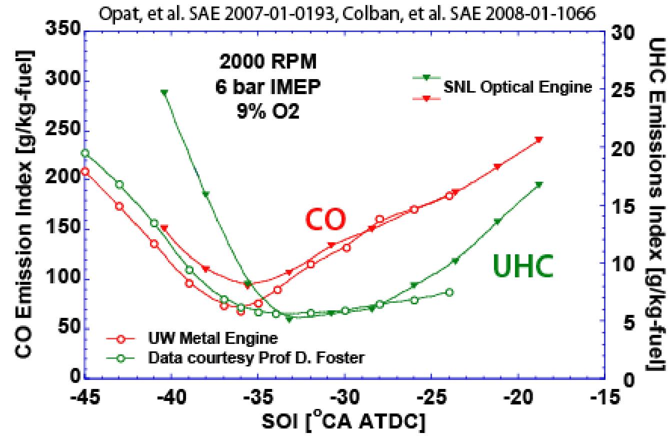
UW:

- Performed simulations of LTC combustion for comparison with experiment
- Examined the impact of IC's and geometric details on flow development
- Improved PRF reduced kinetic mechanisms and developed new mechanisms for alternative fuels
- Incorporated PAH chemistry into reduced chemical mechanisms and developed new soot models
- Developed multi-component vaporization models

Facility and operating conditions

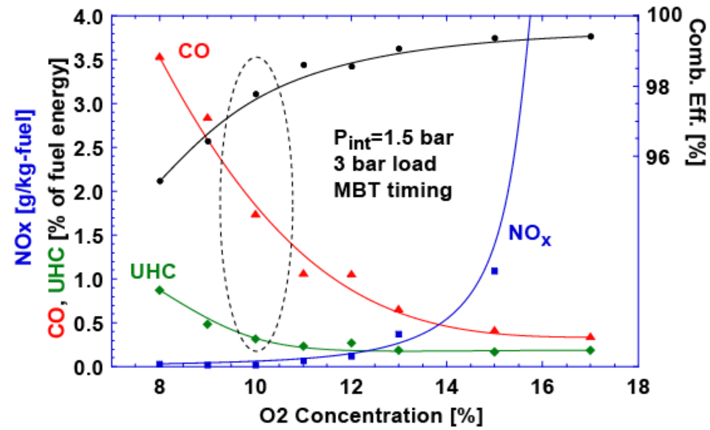


The optical engine matches a metal test engine at UW



The combustion ***and the emissions*** of the metal engine are well reproduced

The optical piston retains the same bowl and piston geometry as the metal engine (including valve-pockets)



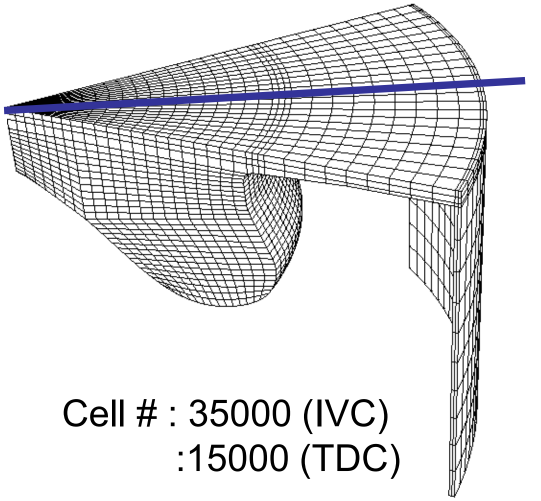
We focus on a dilute, light-load, PCI-like operating condition with rising CO and UHC emissions (ϕ_{intake} = 0.70)

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)
NO_x 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

Computational grid at TDC

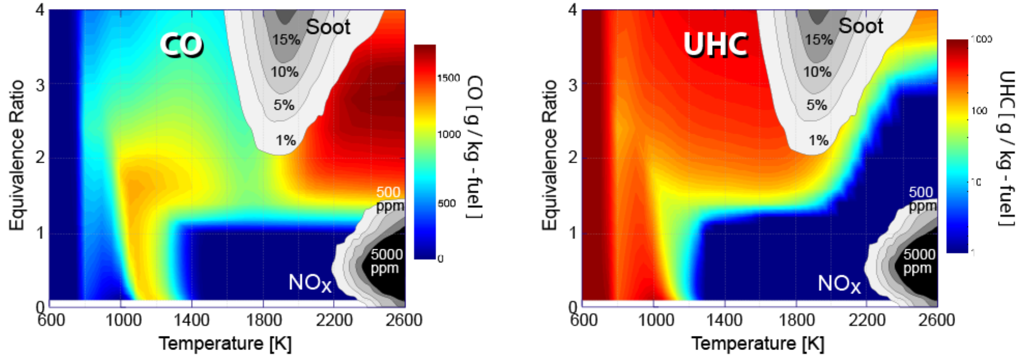


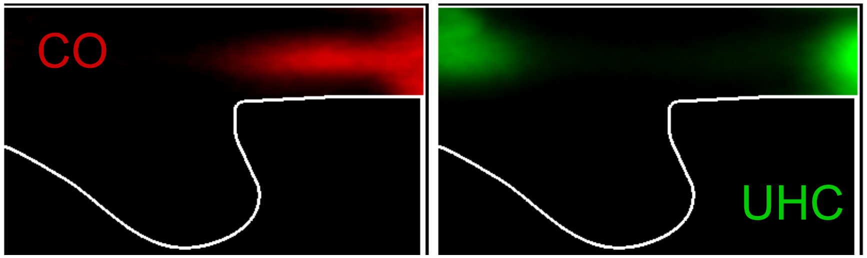
ERC grid-size and time-step independent models (ref. SAE 2008-01-0970)

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

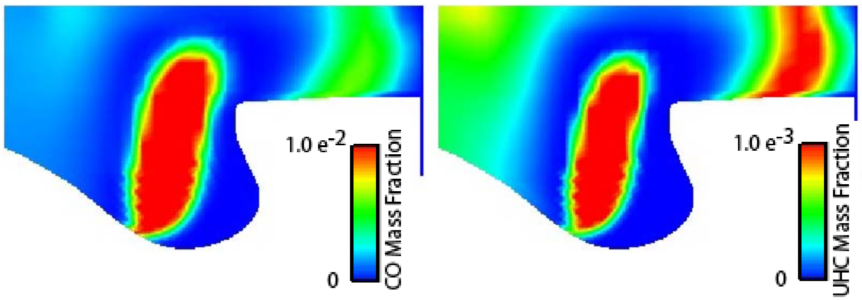
Recap of technical accomplishments in FY07-08

Homogeneous reactor simulations with detailed chemistry clarified expected impact of ϕ, T, and EGR rate on CO and UHC oxidation





Clearance volume CO and UHC measurements identify near-injector and squish regions as significant emission sources

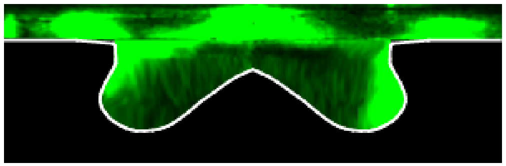


Simulation results exhibit promising agreement, but there are notable differences:

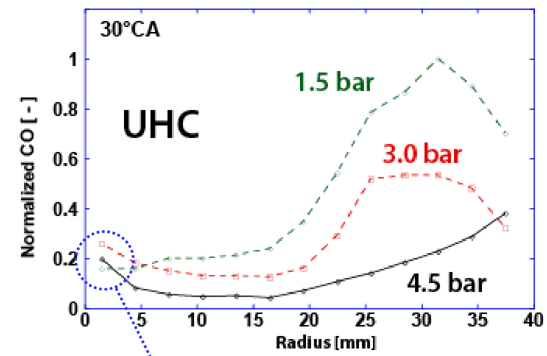
- CO and UHC exiting bowl
- UHC from ring-land crevice

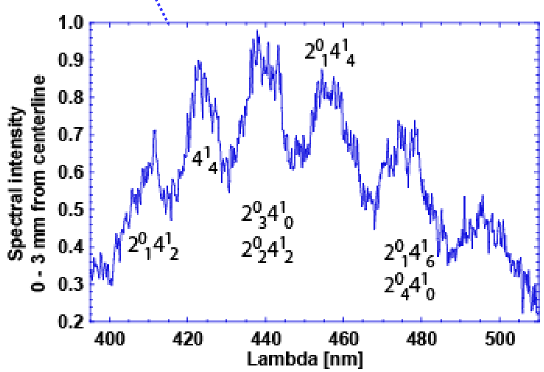
This year, we focused on identifying sources of UHC throughout the combustion chamber

2-d PLIF images:

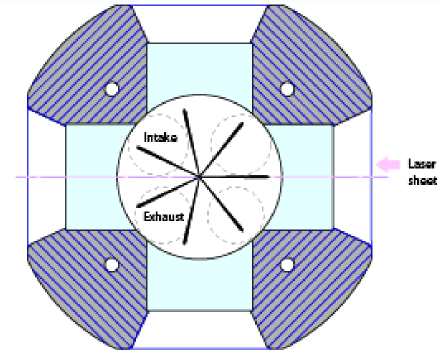


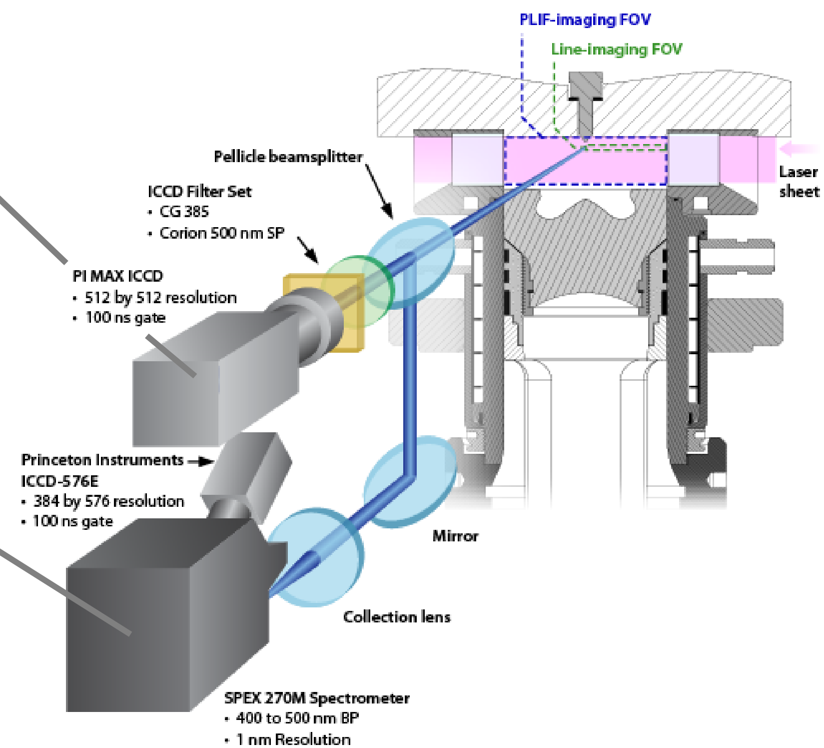
1-d spectrally-resolved:





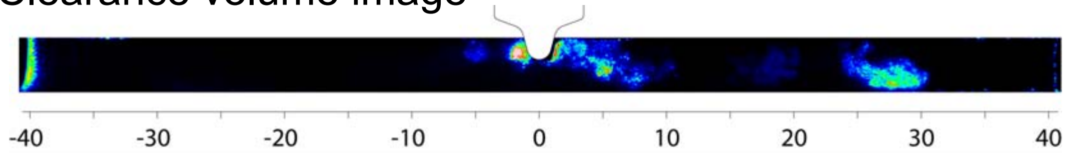
PLIF imaging with 355 nm excitation allows visualization of CH_2O, PAHs, and parent fuel compounds





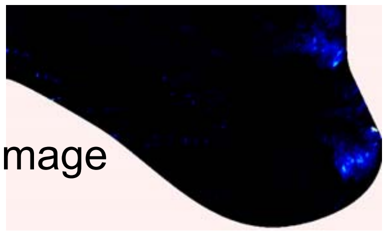
We have also employed elastic scattering to visualize liquid fuel and measure flow (PIV)

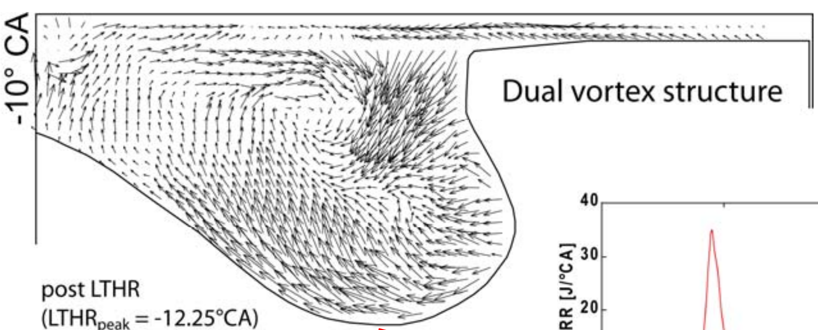
Clearance volume image

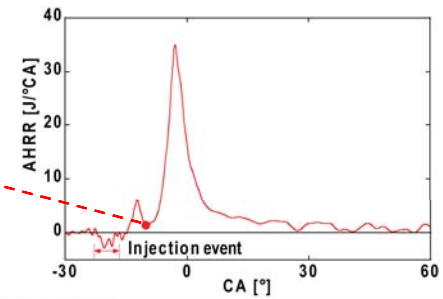


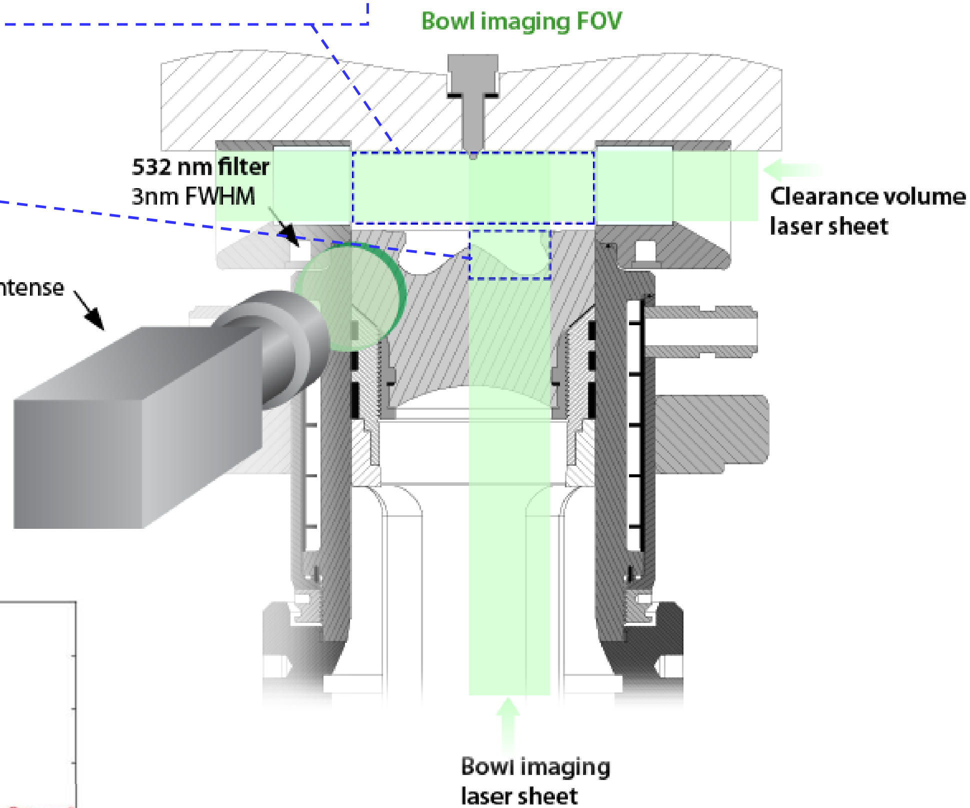
SOI = -31.1°aTDC
Crank angle shown: -15°aTDC

Bowl image



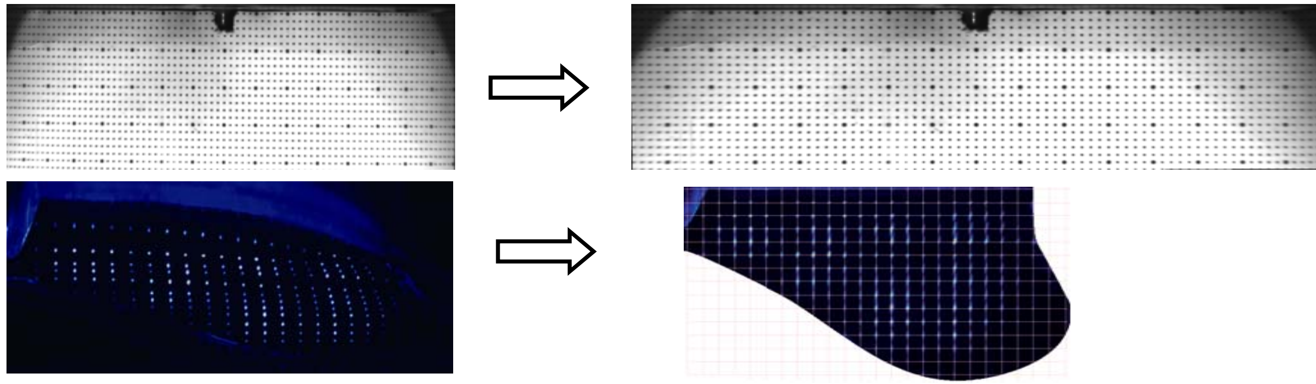




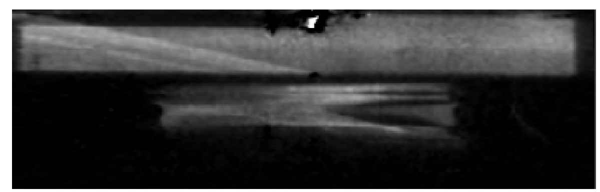


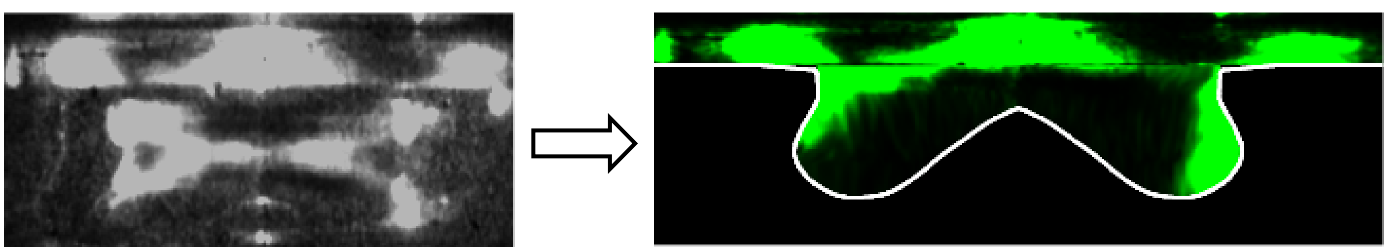
Both PLIF and elastic scatter images are distortion corrected

Calibration images are used to compute separate distortion corrections for the bowl and clearance volumes



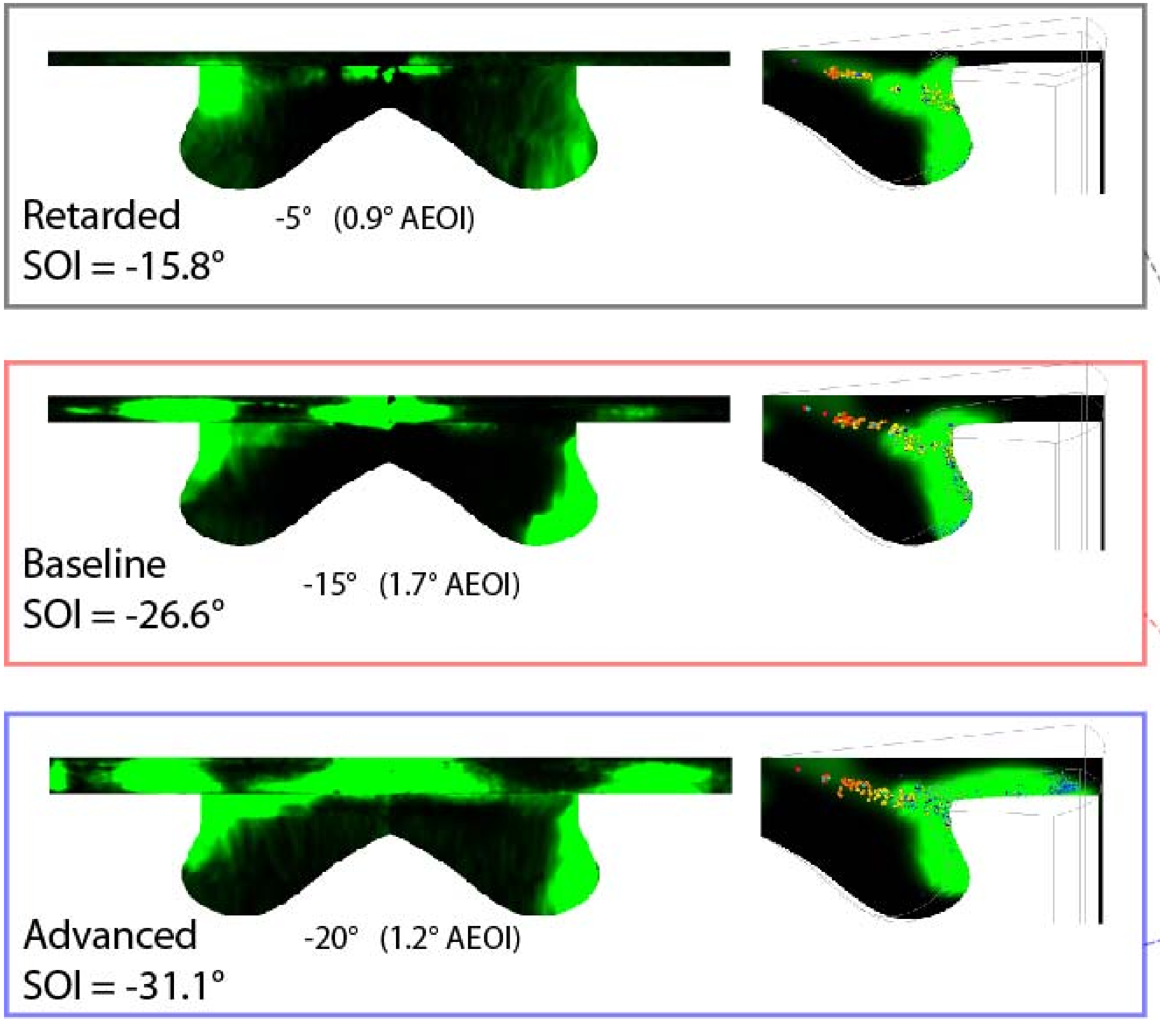
Flat-field images are also obtained to correct for laser sheet intensity variations:



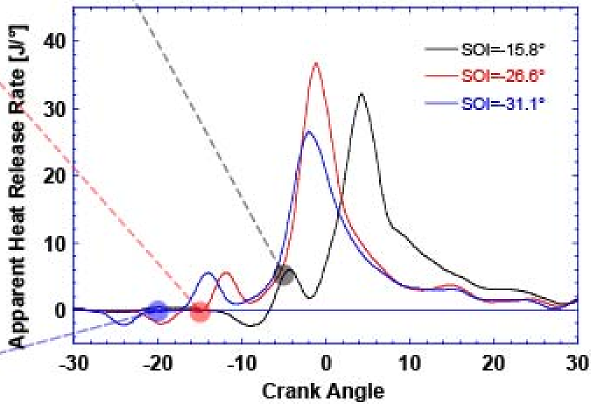


After correction a nearly seamless, complete view of the diametral plane is obtained

Both liquid and vapor fuel contribute to the images during the ignition dwell period

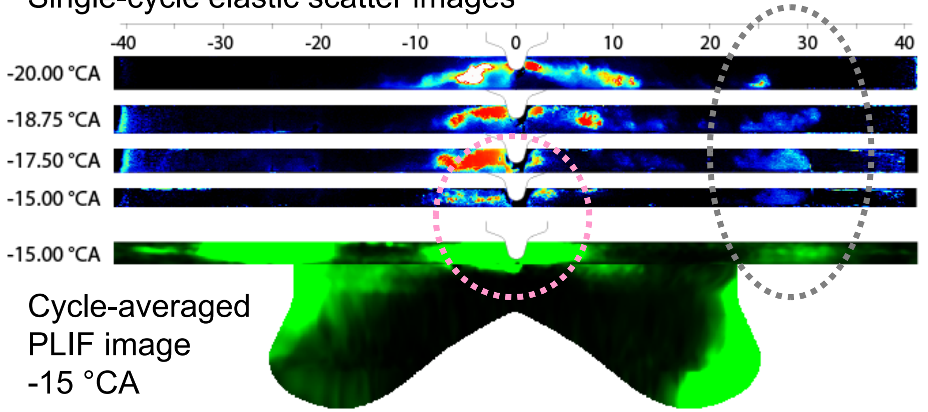


Vapor phase fuel distributions are qualitatively well-captured by the simulations for a variety of injection timings



Elastic scattering identifies those regions where liquid fuel is found

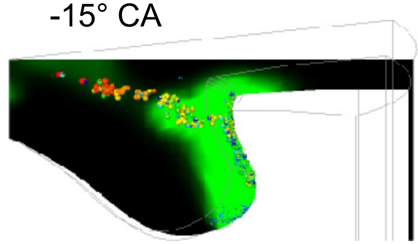
Single-cycle elastic scatter images



Cycle-averaged PLIF image -15 °CA

Baseline: SOI = -23.1°; EOI = -16.7°

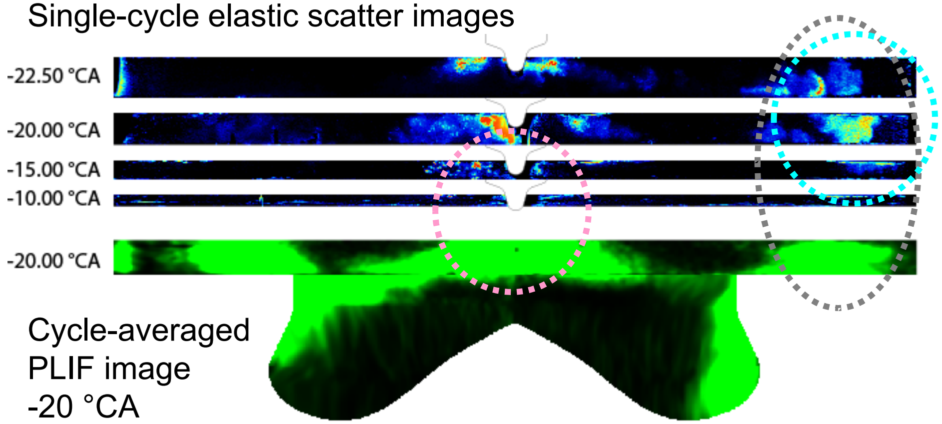
Simulation results at -15° CA



Maximum UHC penetration into the squish volume correlates closely with liquid penetration

Model captures liquid penetration well for advanced SOI, less so for the baseline SOI

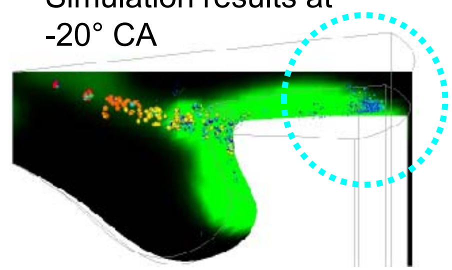
Single-cycle elastic scatter images



Cycle-averaged PLIF image -20 °CA

Advanced: SOI = -27.6°; EOI = -21.2°

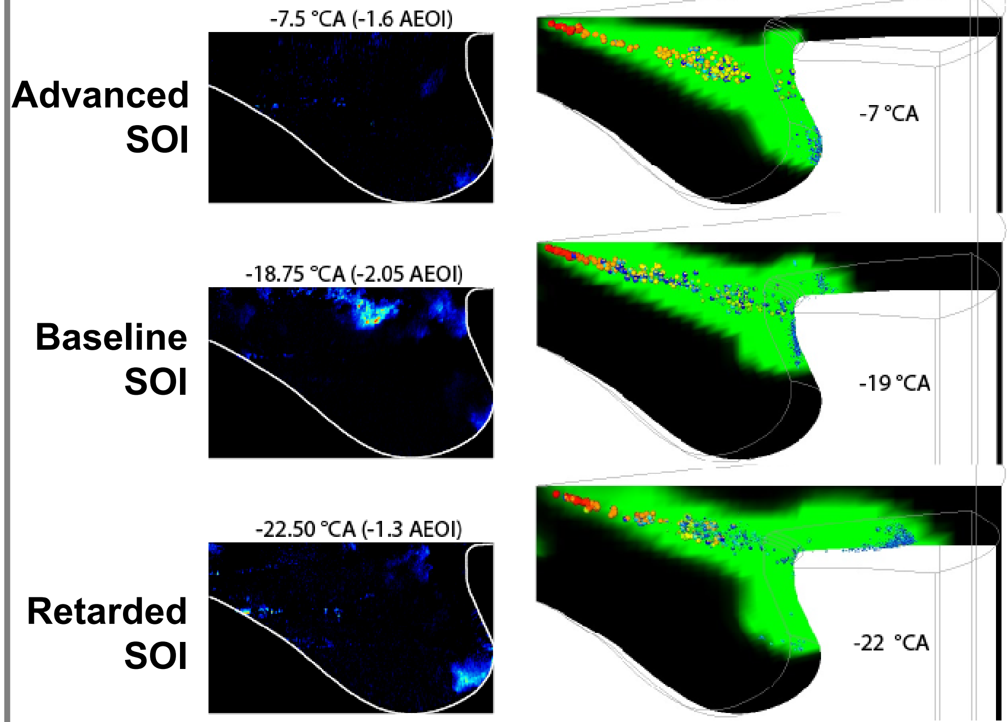
Simulation results at -20° CA



Typically, liquid fuel persists near the injector well after EOI

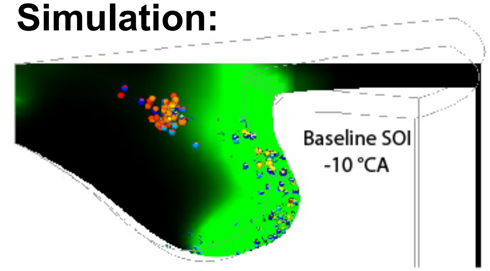
Liquid fuel can also be observed within the bowl

Elastic scatter images: **Simulation results:**

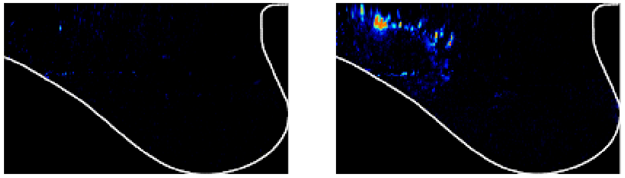


Liquid penetration along the bowl periphery typically appears to be under predicted, although liquid is not observed experimentally in every cycle

Simulation:



Elastic scatter images:



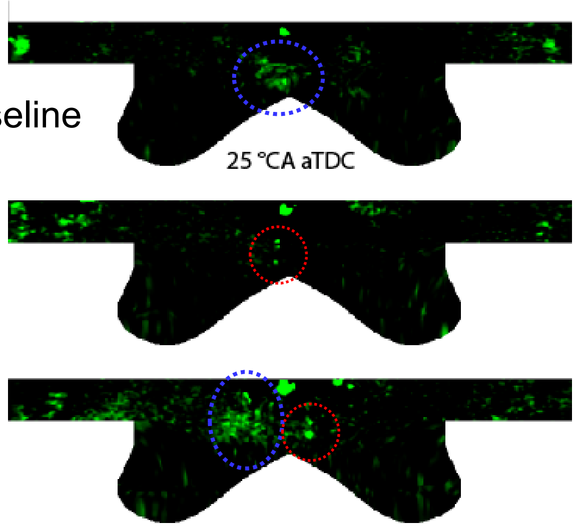
Typical image

Atypical image (1:50)

After the end of injection, little liquid is generally observed along the spray path

Late in the cycle, one source of engine-out UHC is found near the injector

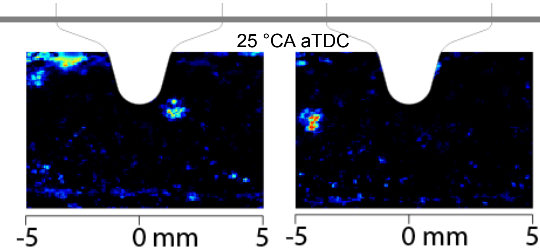
Baseline SOI



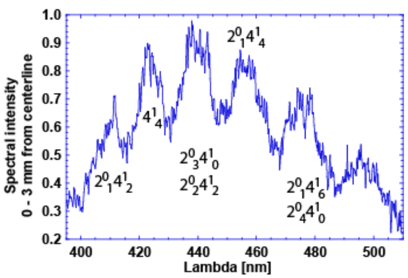
Single cycle PLIF images show that centerline UHC is associated with two sources:

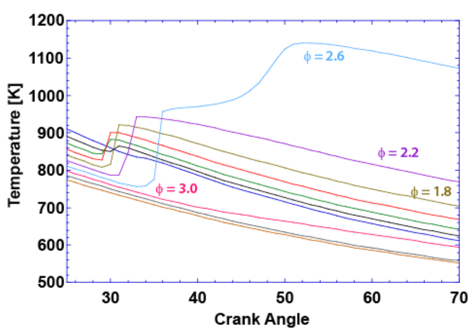
- Diffuse vapor clouds
- Discrete droplets

Elastic scatter images also show fuel droplets near the injector



CH_2O spectral signature observed from fluorescence near the injector is not indicative of lean mixtures…



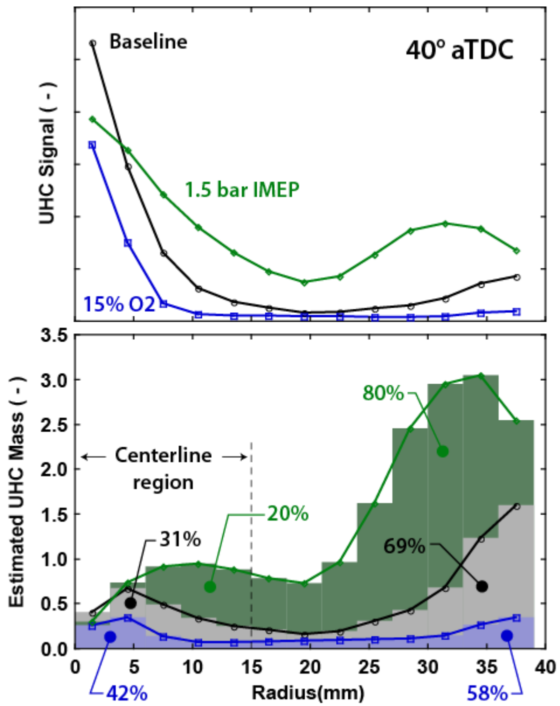


…simulations indicate that fuel introduced at 25° aTDC will not burn completely for any ϕ

Note that late-cycle nozzle dribble is typically not modeled

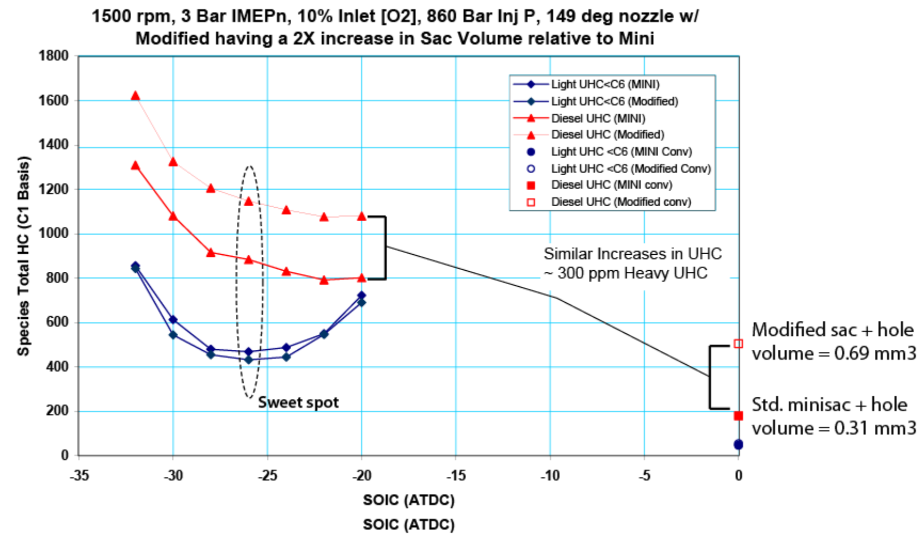
The centerline region and/or nozzle dribble may account for ≈15–30% of engine-out UHC

SNL LIF data in clearance volume



- Assume LIF signal ~ UHC concentration
- Lower figure is volume weighted

Metal engine data from UW (Foster)

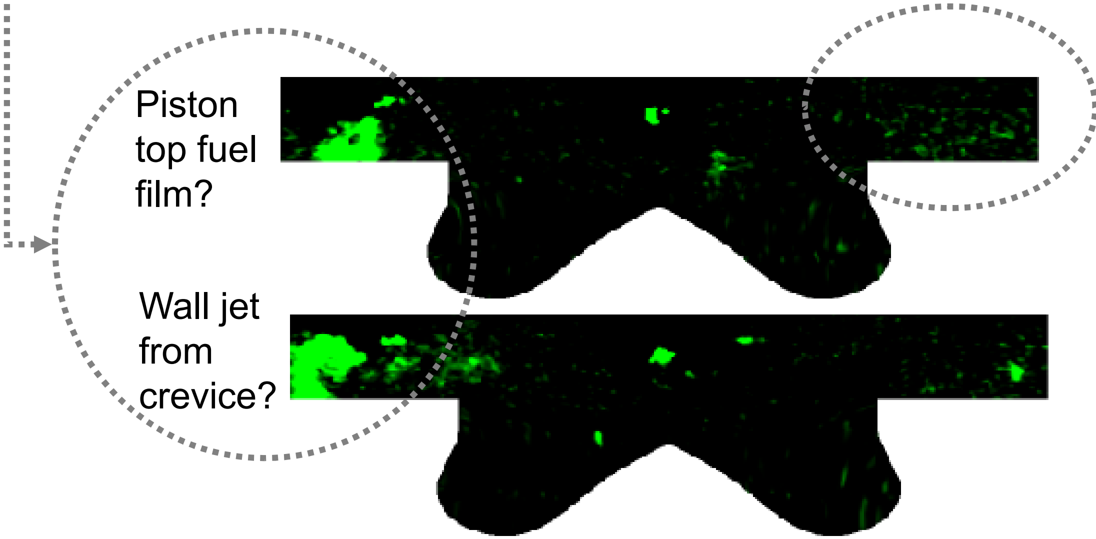


- Sac volume mainly contributes heavy UHC
- The sac volume contribution can be estimated as

$$\frac{200 \text{ ppm}}{450 + 880 \text{ ppm}} \approx 15\%$$

UHC within the squish volume also contributes to engine-out UHC

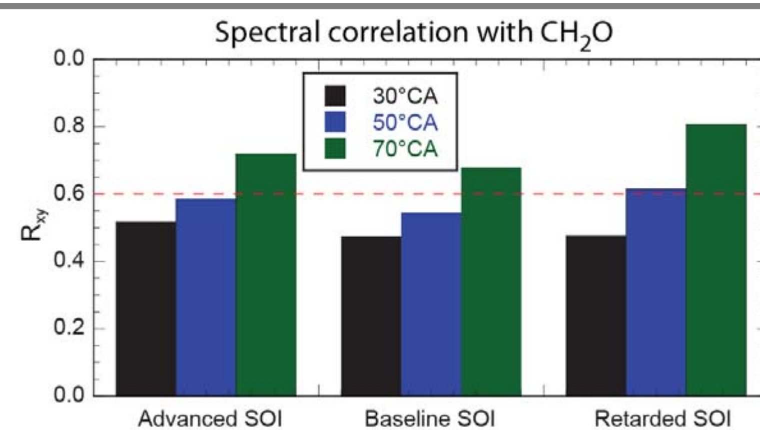
Intense UHC fluorescence is observed within the squish volume on approximately 20% of the cycles



More frequently (all cycles), diffuse UHC is observed

Single-cycle PLIF images
Baseline SOI, 25 °CA aTDC

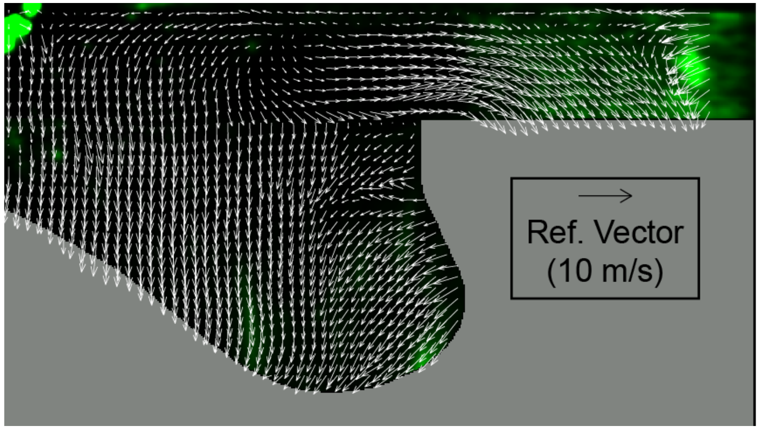
Spectral characteristics suggest the squish volume UHC is initially largely unreacted fuel. Significant CH_2O forms later



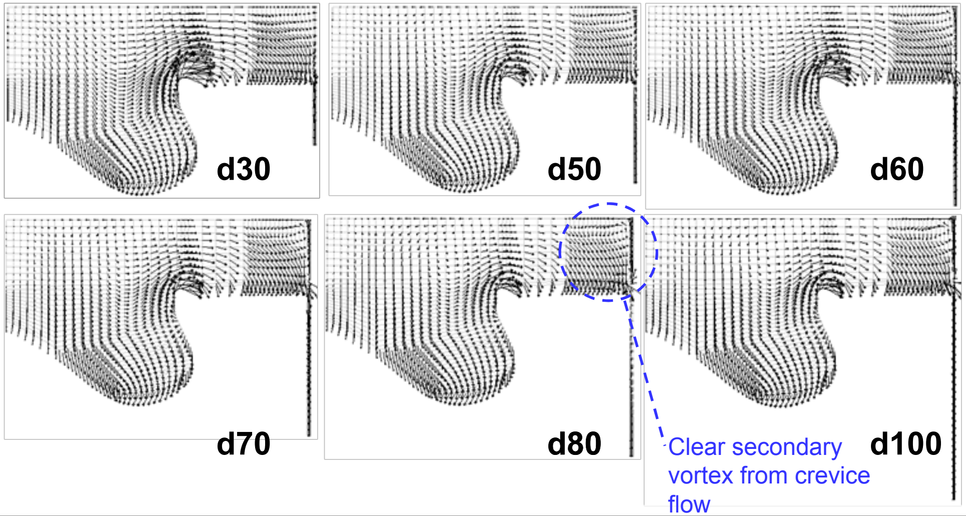
Accurately simulating crevice flows will be crucial to capturing the squish volume UHC (and CO)

Crevice flows:

- Transport UHC into the crevices
- Transport and mix UHC with bulk gases during expansion
- Represent one of the major differences between optical and metal engines



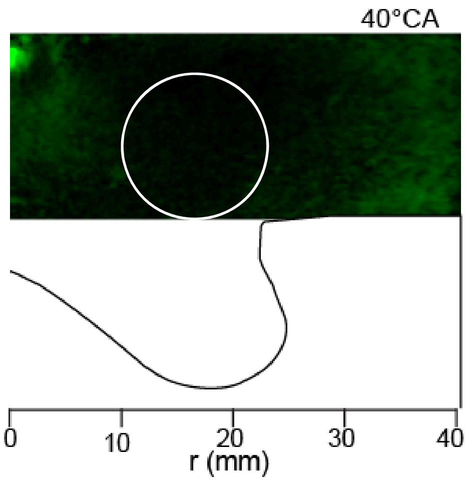
Cycle-averaged UHC and flow field



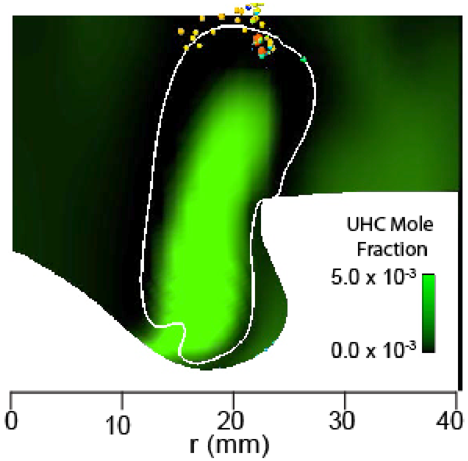
UW is currently investigating the impact of crevice geometry on the crevice flows

- With sufficiently large crevice volumes, flow structures matching the measurements are reproduced
- Turbulence model and grid resolution are secondary factors impacting the predictions

A third predicted source of UHC is overly rich (under mixed) fuel within the bowl

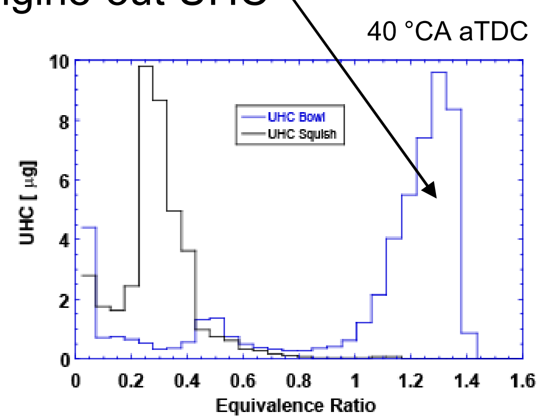


50-cycle averaged PLIF image

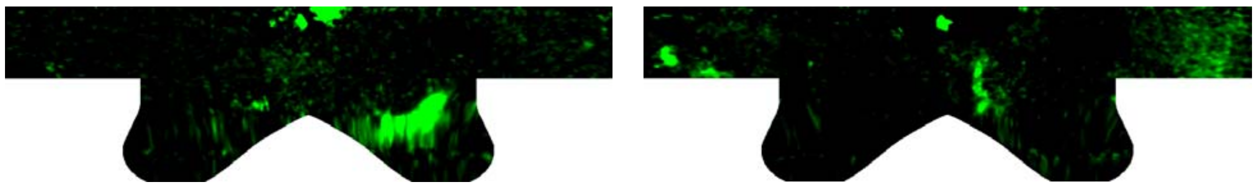


Simulation UHC distribution

Predicted mass density histograms indicate this is the dominant source of engine-out UHC



The experimental images do not exhibit this dominant source, though single cycle-images do show occasional bright fluorescence deep in the bowl:



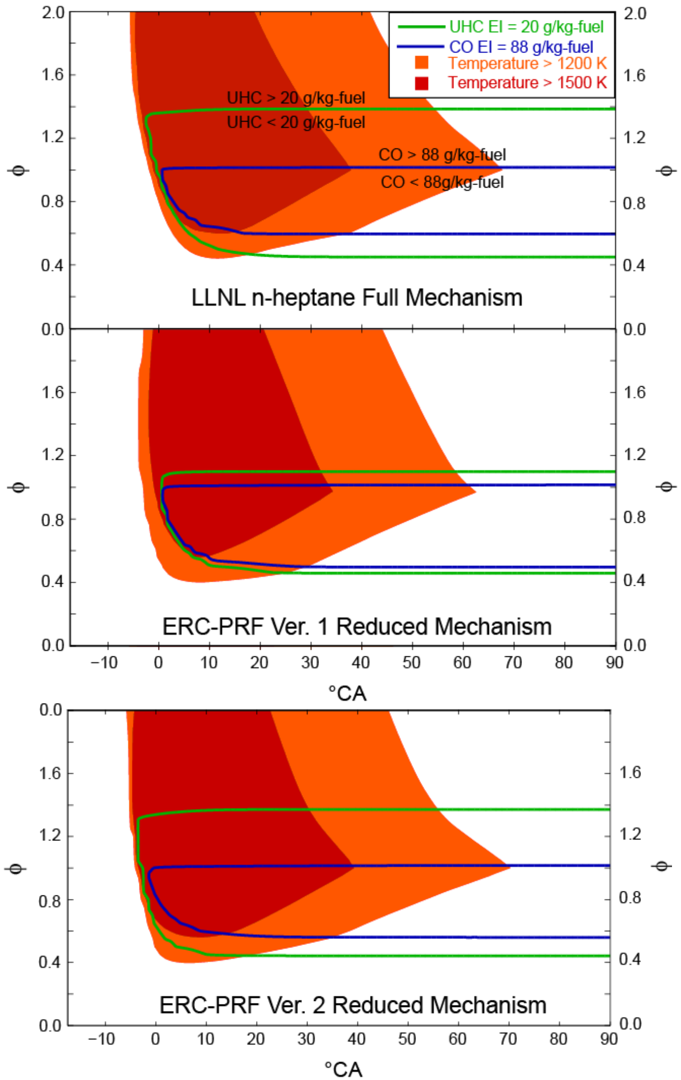
PLIF images at 30 °CA aTDC

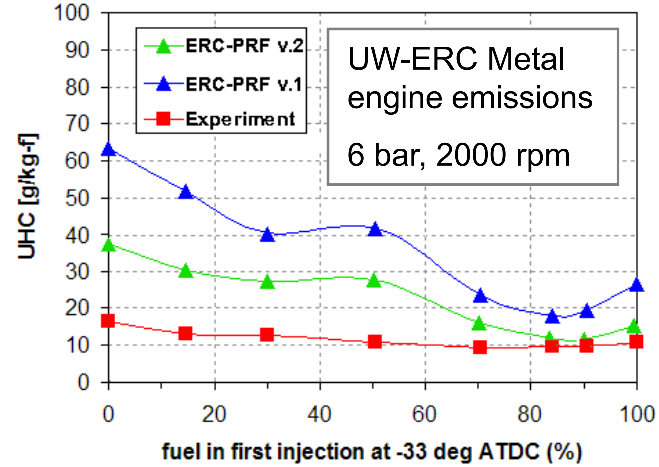
The reduced chemical mechanism was thought to be a possible source of this discrepancy

LLNL n-heptane mechanism
- 561 species
- 2539 reactions

ERC-PRF reduced mechanism
- 39 species
- 129 reactions

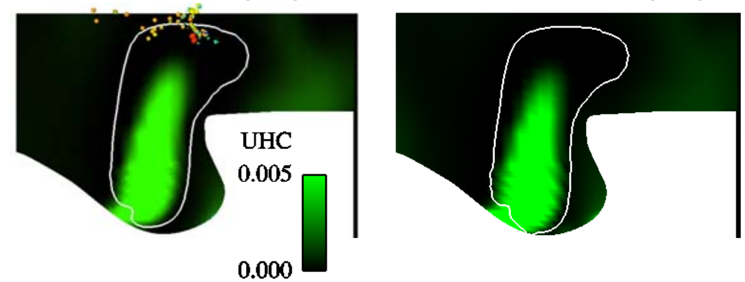
ERC-PRF (v.2) reduced mechanism
- 42 species
- 131 reactions





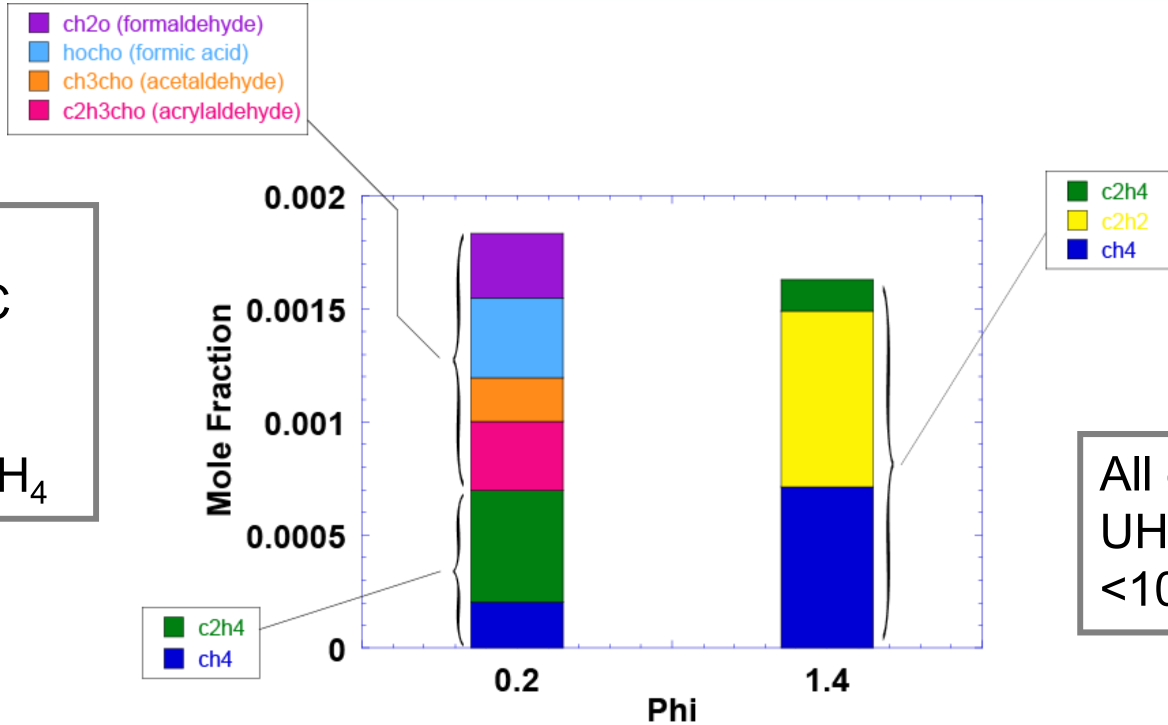
Although the revised mechanism significantly improves agreement with engine out emissions, it does not resolve the in-cylinder discrepancy

ERC-PRF (v.1) **ERC-PRF (v.2)**



Experimental detection of C_2H_2 may help resolve this discrepancy

Typical lean mixture UHC consists of aldehydes, C_2H_4, and CH_4



Typical rich mixture UHC consists of C_2H_2, C_2H_4, and CH_4

All other UHC and UHCO species <100 ppm

The 355 nm PLIF diagnostic responds to:

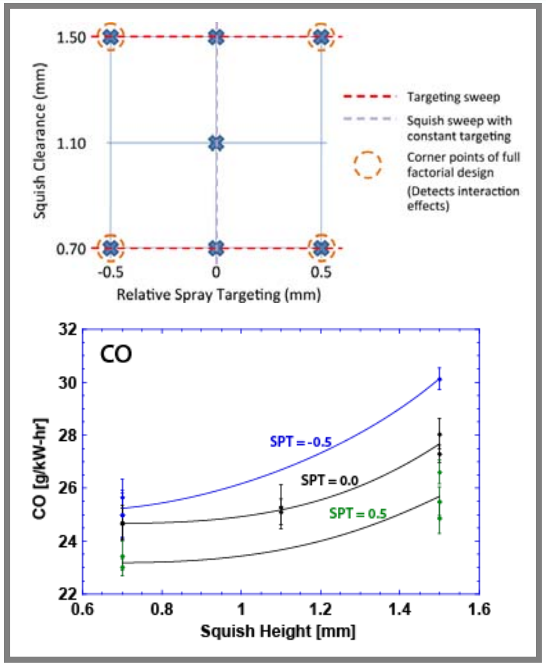
- CH_2O (lean mixtures)
- PAHs ($\phi > 2$)
- Fluorescent compounds in parent fuel

We are currently developing optical techniques to detect C_2H_2

CO measurements within the bowl are also being pursued

Future work – SNL

- Continue to investigate discrepancies between measured and simulated in-bowl UHC (and CO) distributions
- Assess the impact of liquid films and fuel effects on squish volume UHC by varying fuel volatility
- Completion of experiment investigating impact of squish height and spray targeting on UHC and CO emissions (in collaboration with Lund University)
- Examine in-cylinder UHC/CO distributions for different operating conditions (load, O_2) and LTC strategies



Generate a "library" of experimental data to validate simulations against

- Continue to develop flow measurement capabilities
  - Investigate impact of valve cut-outs on flow and combustion development
  - Develop techniques for compensating for out-of-plane motion on the bowl flows
- Pursue investigations of multiple injection strategies on mixing and LTC combustion—focus on close-coupled post injections

Future work – UW

- Continue to investigate discrepancies between measured and simulated in-bowl UHC (and CO) distributions
- Continue to investigate impact of initial conditions and detailed geometry on flow structures
  - Crevice flows
  - Piston top valve pockets and head valve recesses
- Continue to improve and extend reduced chemical kinetic mechanisms to alternative fuels
- Complete implementation of multi-component fuel vaporization models and, coupled with new kinetic mechanisms, investigate fuel effects on combustion and emissions processes

  Compare simulation results to SNL, ORNL, UW engine data
- Assess new soot models against engine soot data from ORNL for both conventional diesel fuel and biodiesel blends

Summary

- Experiments investigating in-cylinder UHC distributions in PCI-type LTC operating regimes have identified several fundamental sources of engine-out UHC (and CO) emissions. The impact of operating parameters and strategies for reducing these emissions are the topics of on-going research
- Detailed comparison of experimental UHC (and flow) distributions throughout the combustion event have identified areas where model development, improvement or careful attention to detail is required:
  - Crevice geometry and flows
  - Spray targeting
  - Piston (and head) liquid film models
  - Nozzle dribble
  - Transient atomization
- This work has identified deficiencies and led to significantly improved reduced-chemistry combustion models

Advances are being made in our fundamental understanding, quantitative experimental techniques, and predictive modeling capabilities—but additional work is required