# HCCI and Stratified-Charge CI Engine Combustion Research

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**U.S. DOE, Office of Vehicle Technologies**
**Annual Merit Review and Peer Evaluation**

**Program Manager: Gurpreet Singh** **Project ID: ace_04_dec**

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

# Overview

## Timeline

- Project provides fundamental research to support DOE/Industry advanced engine projects.
- Project directions and continuation are evaluated annually.

## Budget

- Project funded by DOE/VT:
  FY08 – $695k
  FY09 – $700k

## Barriers

- Extend HCCI (LTC) operating range to higher loads.
- Improved understanding of in-cylinder processes.
- Control HC & CO emiss. at low loads.

## Partners / Collaborators

- Project Lead: Sandia ⇒ John E. Dec
- Part of Advanced Engine Combustion (AEC) working group:
  - 15 Industrial partners: auto, engine & energy
  - 5 National Labs & Univ. of Wisconsin
- GM – bimonthly meetings & discussion
- Chevron – funds complementary project
- LLNL – 1) support kinetic-mechanism devel., 2) CFD modeling, & 3) cooperative project on detailed exhaust speciation.

# Objectives

**<u>Project objective</u>: to provide the fundamental understanding (science-base) required to overcome the technical barriers to the development of practical HCCI and HCCI-like engines by industry.**

## FY09 Objectives:

- Determine the development of natural thermal stratification in an HCCI engine, using planar-imaging thermometry.
  - Thermal-imaging diagnostic developed as part of this task.
- Evaluate the potential of intake boost for extending the high-load limit of HCCI by using EGR to control combst.-phasing advance – multi-year task.
  - <u>FY09</u>: Determine potential of boost with EGR for gasoline at rep. engine speed.
- Determine the performance of ethanol as a fuel for HCCI engines.
  - Conducted cooperatively with M. Sjöberg in the Advanced SI-Engine Fuels Lab.
- Support CFD modeling and the development/improvement of chemical-kinetic mechanisms for HCCI at LLNL ⇒ provide data and analysis.

# Milestones

**FY2008**

- Complete analysis of detailed exhaust-gas speciation measurements for iso-octane. (February 2008) – Status: Completed
- Determine the potential benefits of EGR for reducing the maximum pressure-rise rate and extending the high-load HCCI limit. (August 2008) – Status: Completed

**FY2009**

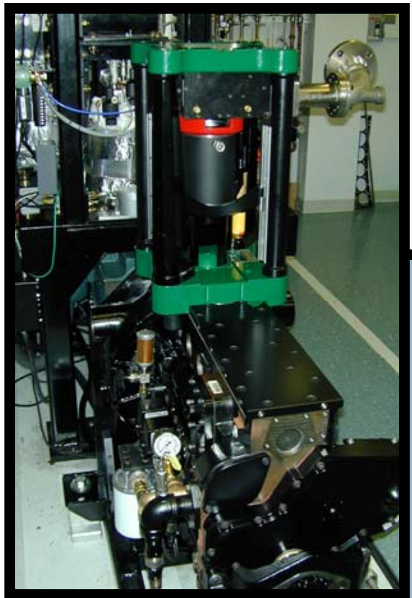
- Determine the magnitude and distribution of the natural thermal stratification in an HCCI engine at a typical operating condition. (February 2009) – Status: Completed.
- Determine the potential of EGR for increasing the allowable intake-pressure boost for gasoline-like fuels, at a representative engine speed. (August 2009) – Status: ~60% complete as of March 2009.

# Approach

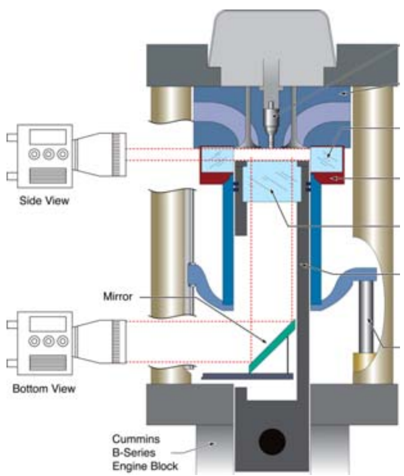
- Use a combination of metal- and optical-engine experiments and modeling to build a comprehensive understanding of HCCI processes.

- Metal engine ⇒ design well-characterized experiments to isolate specific aspects of HCCI/SCCI combustion & relationships between parameters.
  - Intake boost: Systematically increase boost ⇒ adjust $T_{in}$ and/or EGR to retard timing to allow max. fueling at each $P_{in}$ without knock, but with good stability.
- Optical engine ⇒ detailed investigations of in-cylinder processes.
  - Thermal stratification (TS): Develop temperature-imaging diagnostic ⇒ Apply to obtain T-map images showing temporal and spatial development of TS.
- Computational Modeling ⇒ supplement experiments by showing cause-and-effect relationships that are not easily measured.
  - Initiating LES modeling with J. Oefelein, Sandia to understand mechanism of TS.
  - In-house CHEMKIN (Senkin) single- and multi-zone kinetic modeling.
  - Collaborate with LLNL to improve kinetic mechanisms, and on CFD modeling.
- Combination of techniques provides a more complete understanding.
- Transfer results to industry.

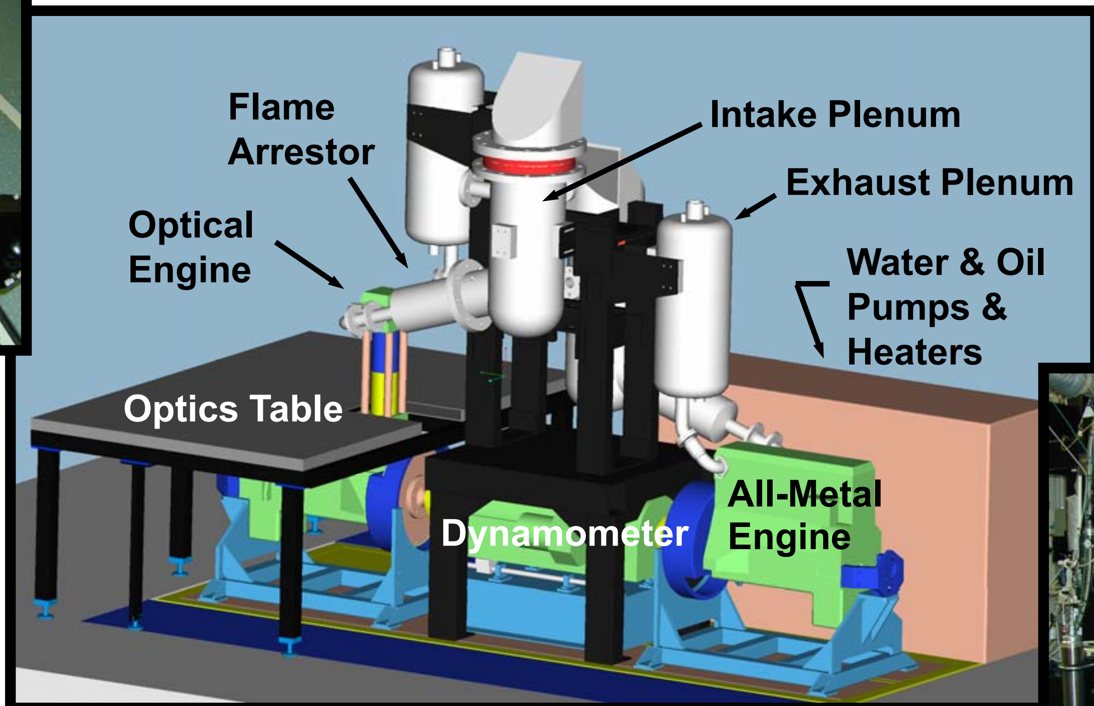
# Sandia HCCI / SCCI Engine Laboratory

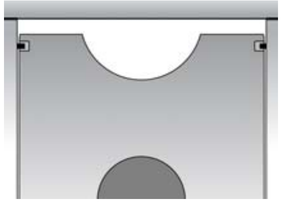


Optical Engine

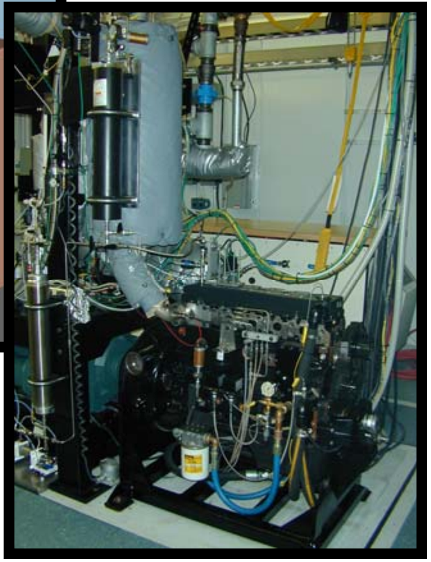



- Matching all-metal & optical HCCI research engines.
  - Single-cylinder conversion from Cummins B-series diesel.



All-Metal Engine



- Bore x Stroke = 102 x 120 mm
- 0.98 liters, CR=14

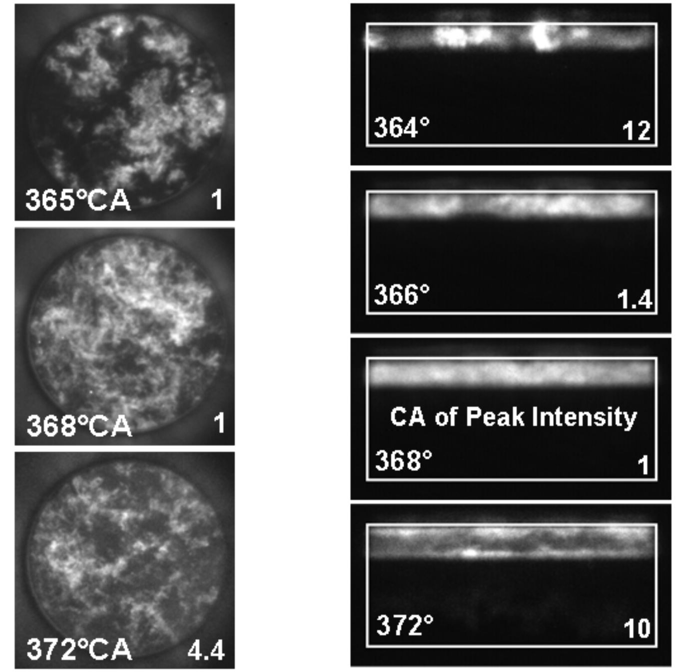
# Accomplishments

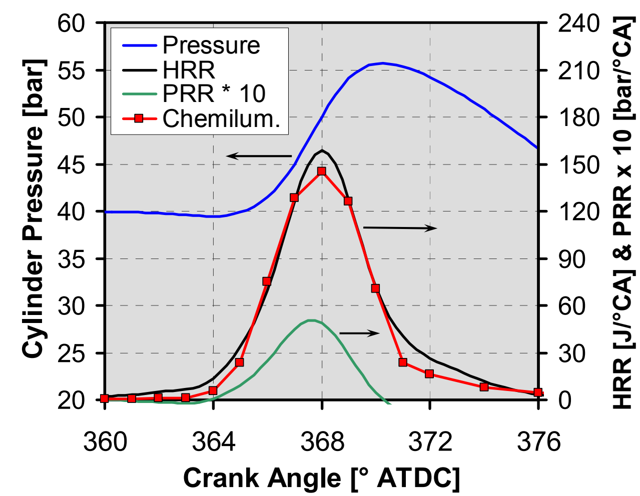
- Determined the evolution of natural thermal stratification in an HCCI engine, including its distribution and magnitude at a typical operating condition.
  - Developed a planar temp.-imaging diagnostic for TS in HCCI engines.
- Conducted initial investigation showing the potential of intake boost for extending the high-load limit of HCCI for gasoline fuel.
  - Showed that EGR is effective for controlling boost-induced timing advance.
  - Achieved a substantial load increase at a rep. 1200 rpm operating condition.
- Determined the behavior of ethanol as an HCCI fuel over a range of operating conditions.
  - Cooperatively with M. Sjöberg of the Advanced SI-Engine Fuels Lab.
- Initiated detailed exhaust-speciation analysis for PRF80 $\Rightarrow$ 2-stage ignition.
  - Project conducted in cooperation L. Davisson at LLNL.
- Supported chemical-kinetic and CFD modeling work at LLNL.
  - Provided data and analysis for: 1) improving chemical-kinetic mechanisms, and 2) CFD modeling of fuel stratification to improve low-load comb. eff. & emissions.

# Importance of Thermal Stratification (TS)

- TS causes autoignition to occur sequentially from hottest region to coldest.
  - Reduces max. pressure-rise rate (PRR).
  - Allows higher fueling without knock.
- Amplify the benefit of the TS by retarding combst. timing ⇒ further increases in load.
- Chemilum. images show:
  - Non-uniformities over whole field of view.
  - Hot reactions start intermittently near the mid-plane.
  - At time of max. PRR most combustion is from bulk gases (central region).
  - BL combust. occurs after max. PRR.

**Bottom-View** **Side-View**

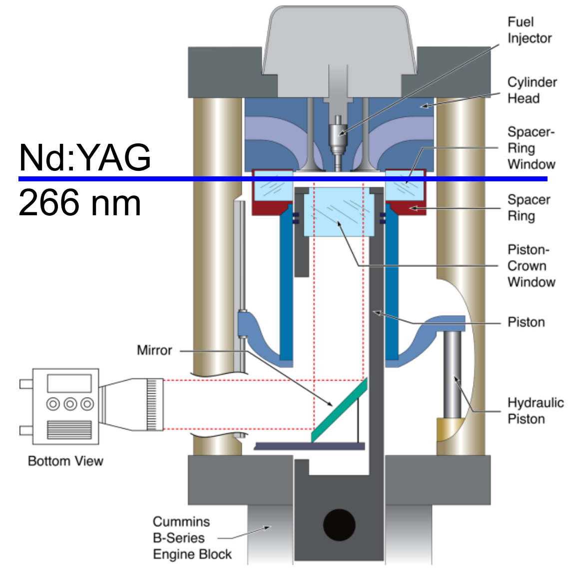



- TS of the bulk gas is critical for high-load HCCI operation.
- Understanding TS is important for increasing the high-load limit of HCCI.

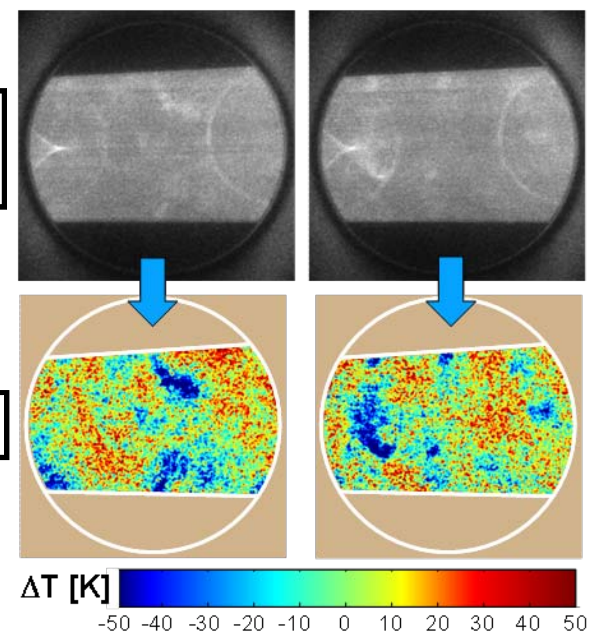
# Planar Imaging Thermometry

- Diagnostic: single-laser toluene PLIF.
  - PLIF intensity varies with temperature.
  - Good sensitivity in desired range, 600 – 1050 K.
- PLIF setup:
  - 2% toluene + 98% iso-octane
  - Laser excitation: 266 nm, 58 mm wide sheet.
  - Intensified camera with 277nm LP & UG5 filters.
  - Run inert with $N_2$ to prevent quenching.
    $\Rightarrow$ OK since TS develops prior to combustion.
- Calibrate temp. sensitivity in-cylinder.
- For well-mixed fueling, variations in PLIF intensity correspond to temp. variation
  - Temperature fluctuations shown relative to the mean of each image.
  - Bright regions in raw image correspond to cold pockets.




**Raw PLIF**

**T-map**

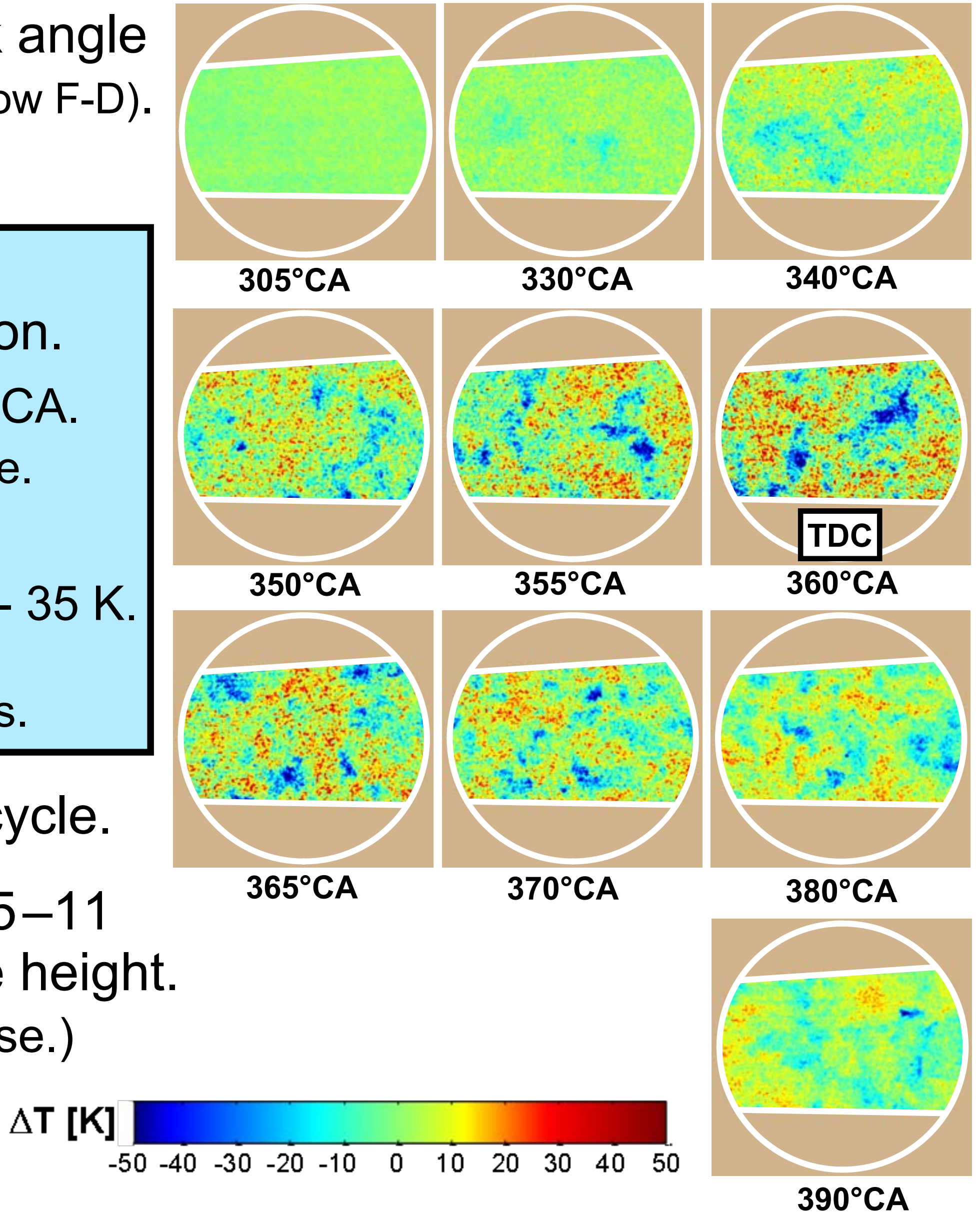


# Temporal Evolution of TS

- Laser elevation adjusted with crank angle to remain in mid-plane (20 - 4 mm below F-D).
  - Representative of <u>bulk gas</u>.

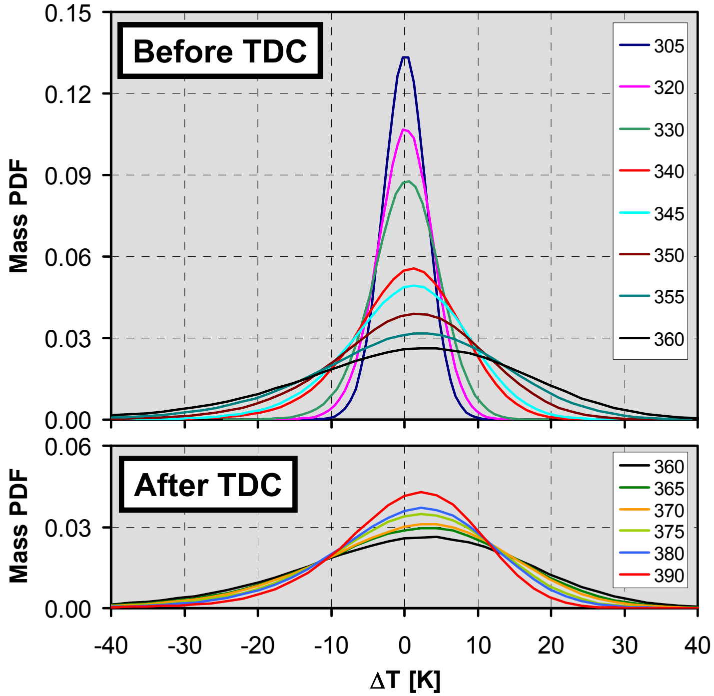
- TS develops progressively as cold pockets convected into central region.
  - Temperature nearly uniform at 305°CA.
    - > Virtually no TS remains from intake.
    - > Insufficient time with $T_{gas} > T_{wall}$.
  - Substantial TS by TDC (360°CA) +/- 35 K.
    - > Sufficient for significant spread in autoignition time of various regions.

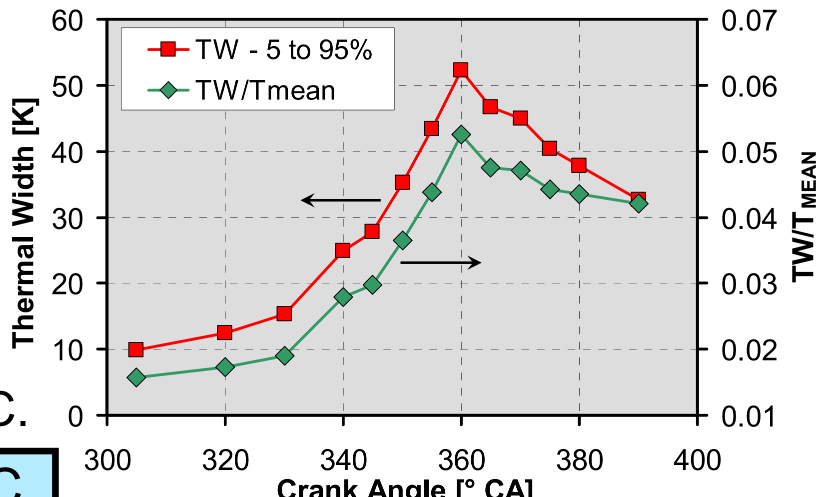
- TS distribution is random cycle-to-cycle.
- Scale of cold pockets near TDC is 5–11 mm, similar to 8mm TDC clearance height.
  (Fine-grain speckle pattern is shot noise.)
- Magnitude of TS appears to diminish after TDC.



# PDF Analysis of TS Images

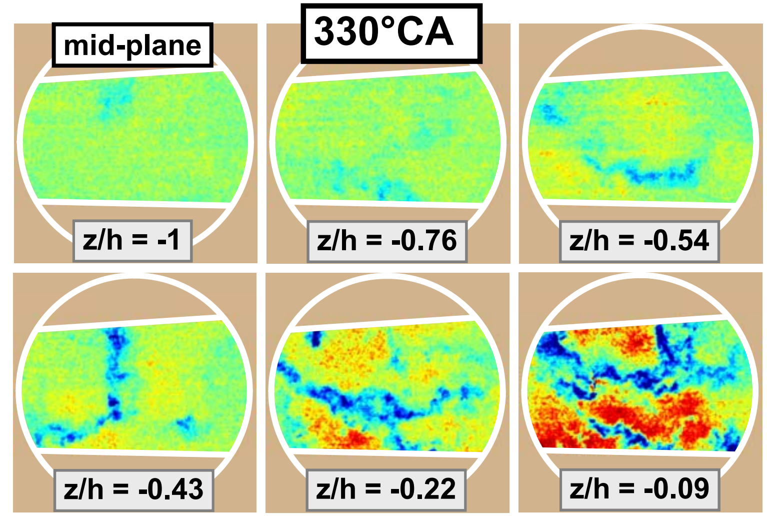
- Apply probability density functions (PDF) to quantify changes in temp. distribution with crank angle.
  - <u>305°CA:</u> PDF very narrow.
    - > Little time for development of TS.
    - > Analysis ⇒ almost all width is shot noise.
  - <u>330 - 340°CA</u>: Significant broadening.
  - <u>340 - 360°CA</u>: Progressive increase.
  - <u>360 - 390°CA</u>: PDF width decreases, in agreement with images. ⇒ cause?
- Define: thermal width (TW) = 5 - 95% of PDF width.
  - Max. TW at TDC ≈ 50 K ⇒ agrees with multi-zone model results.
- Normalize by $T_{MEAN}$ to remove effects of compression & expansion.
  - Reduces, but not eliminate TW decrs. ATDC.
- **Heat transfer dominant ⇒ changes at TDC.**



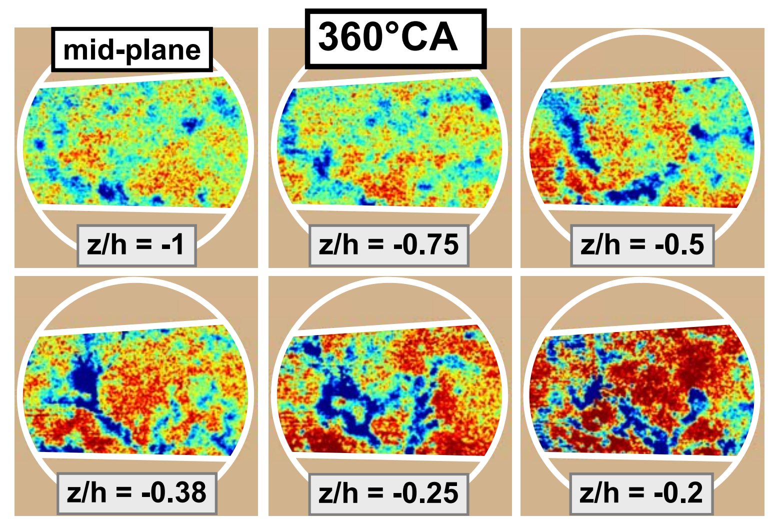



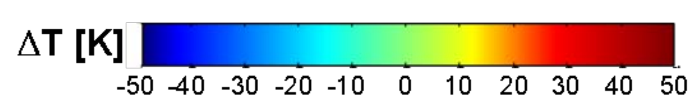
# Thermal Distribution of Boundary Layer (BL)

- Incrementally scan laser from mid-plane to outer BL (to 0.8 mm below firedeck).
- <u>330°CA</u>: bulk-gas temp. is nearly uniform. $\Rightarrow$ Significant TS only for $z/h \geq -0.43$.
- <u>360°CA</u>: TS developed throughout bulk gas. $\Rightarrow$ TS greater in outer BL, $z/h \geq -0.5$.
- Avg. T profiles also show deficits for these z/h.

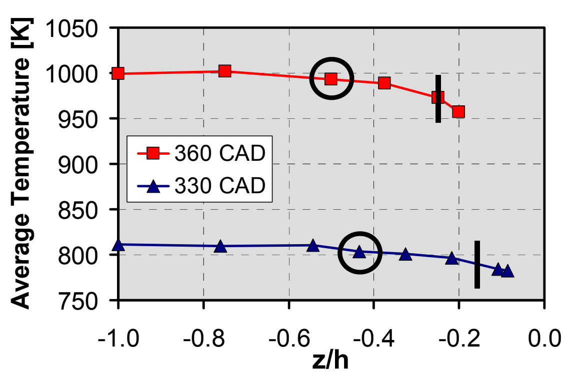



- TS progresses inward from wall, 330°→360°
- Most BL temp. deficit occurs in last 0.8 mm at the wall $\Rightarrow$ drops to $T_{wall} \approx 400$ K.



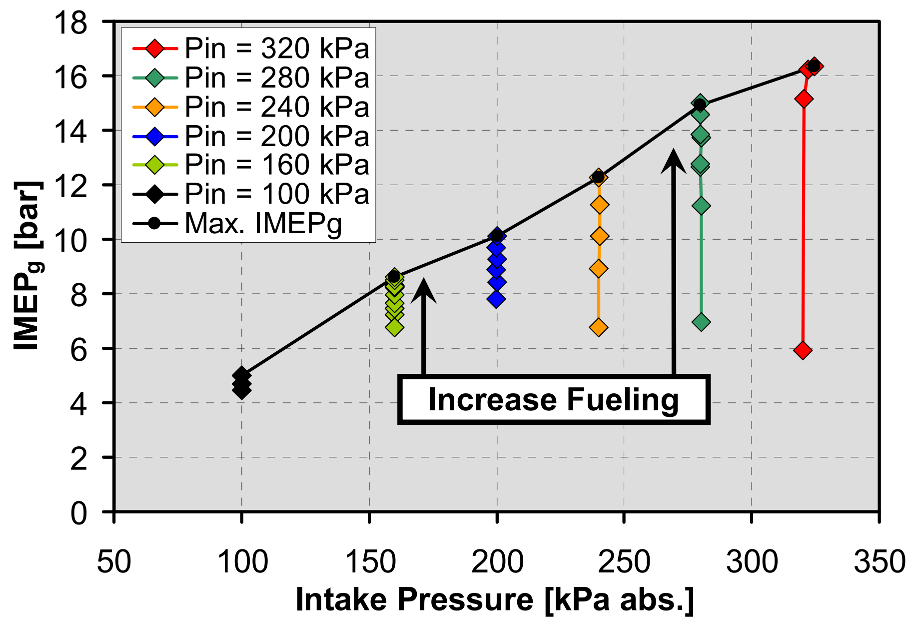




- BL thickness based on a 5% deficit from centerline value $\Rightarrow$ 1-1.5mm.
- Agrees with previous chemilum. & PLIF studies.

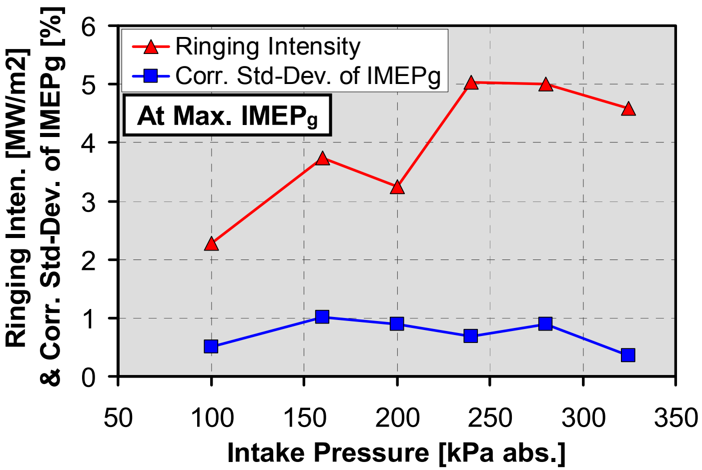


# Intake Boost for Extending High-Load Limit

- Investigate the potential of boosting for extending HCCI to higher-loads.
  - Required to match full-load diesel or SI.
- Current work: gasoline, 1200 rpm.
- Boost enhances autoignition ⇒ advances comb. timing ⇒ Knock!
  - Compensate with reduced $T_{in}$.
  - For $P_{in}$ > 160 kPa, $T_{in} \rightarrow T_{amb}$ ⇒ limits allowable fueling.
- Add cooled EGR to further slow autoignition.



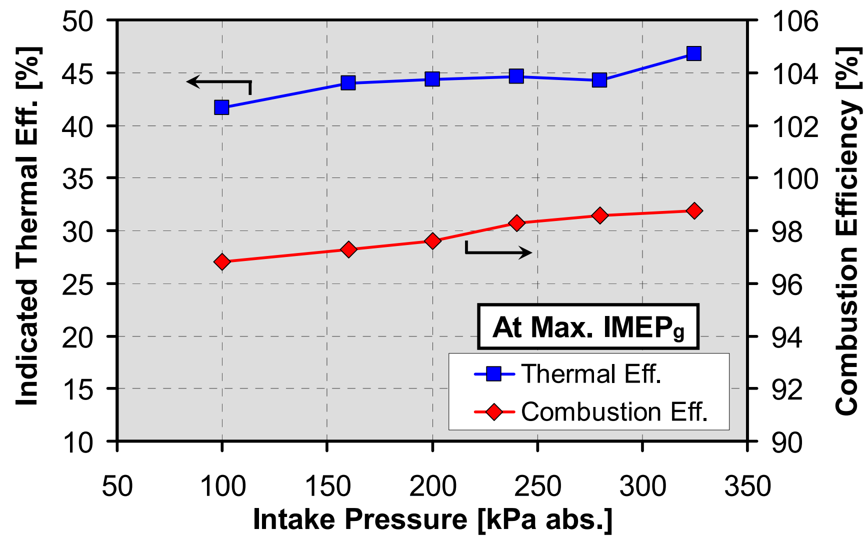

- Achieved **$IMEP_g$ = 16.3 bar**, $P_{in}$ = 324 kPa.
  - Very high $IMEP_g$ for HCCI/LTC, convent'l fuel.
  - Near stoich., C/F = 38.5, EGR = 60%, $P_{exhaust}$ = 326 kPa, $T_{exhaust}$ = 407°C.
- Ringing ≤ 5 MW/m², No Knocking.
- Std-Dev of $IMEP_g$ ≤ 1%, very good stability.

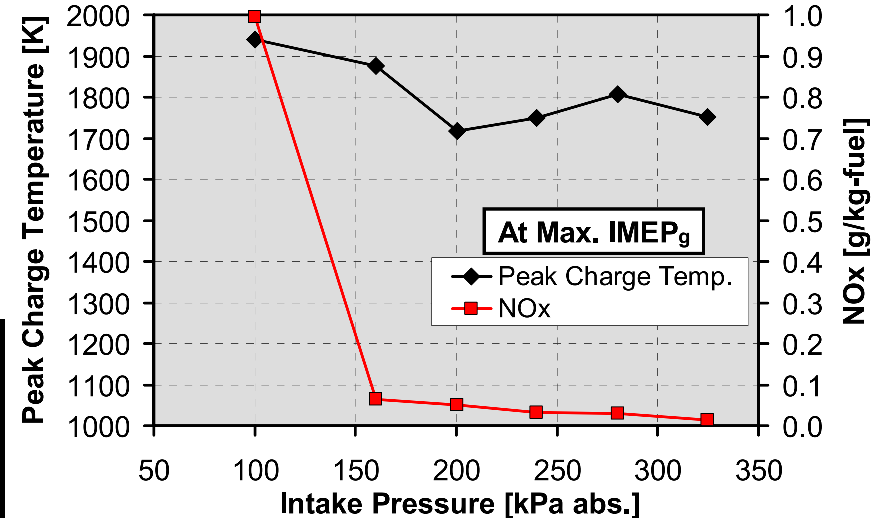


# Efficiency and NOx for Boosted High-Load

**For maximum IMEPg at each boost**

- Indicated Thermal Eff. increases slightly with boost. ⇒ Th. Eff. ~45%.
- Combustion Eff. increases, 97→ 99%.
  - Higher wall temps. ⇒ improve combst.
  - Increased EGR reduces HC & CO emiss.
- NOx emissions below US-2010 stds. (should also meet tier II, bin 5).
  - Extremely low for all boosted cases ( < 0.1 g/kg-fuel, ~1-2 ppm).
- Correlates with low peak charge temp.
  - NOx higher for $P_{in}$ = 100, $T_{peak}$ > 1900K.

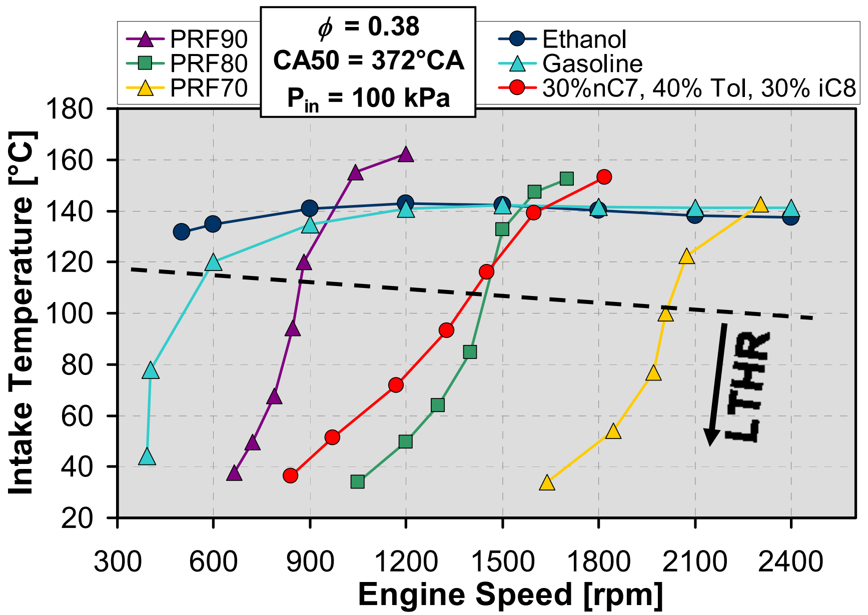


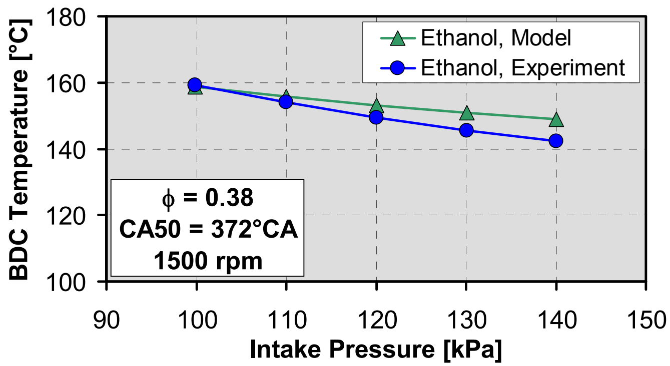

- For max. $IMEP_g$ = 16.3 bar, $P_{in}$ = 3.2 bar.
  - Ind. Thermal Eff. = 47%
  - Comb. Eff. = 99%
  - NOx = 0.015 g/kg-fuel, $T_{peak}$ = 1750 K.

# Ethanol as an HCCI Fuel

- Ethanol is a component in most pump gasoline (0 – 15% fraction).
  - Also being considered as an alternative fuel at levels up to 85%.
- Important to understand ethanol's potential for HCCI.
  - Ignition quality ⇒ RON = 107, MON = 89
  - Effect on performance and operating range, *i.e.* speeds, boost, etc.
- Speed sweep ⇒ CA50 = 372°CA
  - Autoig. similar to gasoline for RPM >900.
  - Most fuels: $T_{in}$ < 100°C as speed is reduced ⇒ indicates LTHR (cool flame).
  - Ethanol shows no LTHR!
- Boost has only moderate effect on $T_{in}$.

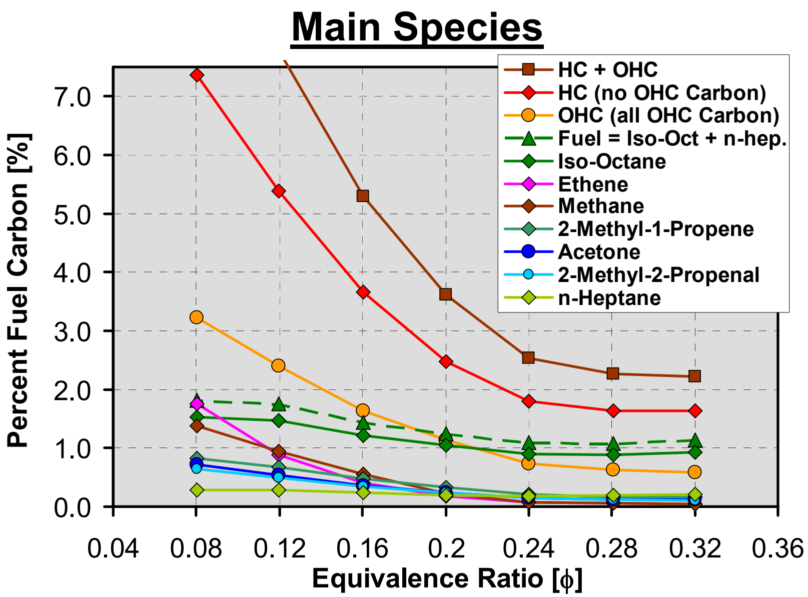


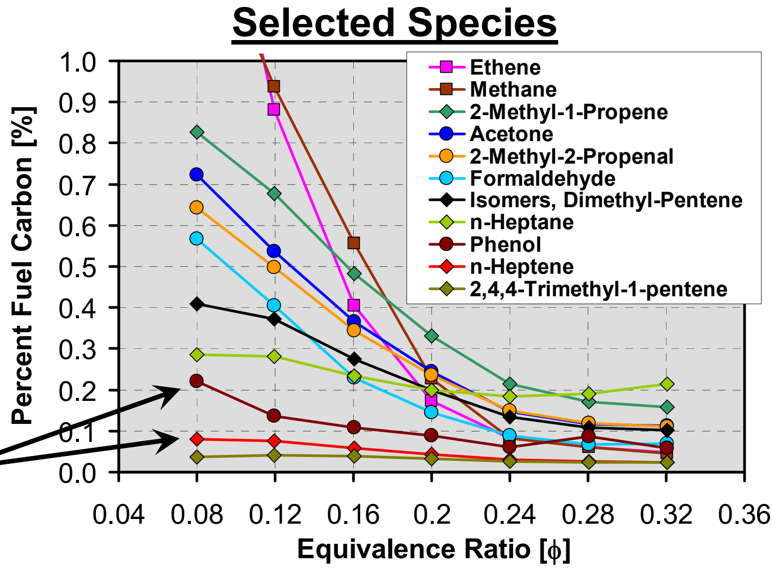

- Performs similarly to gasoline, conds. studied.
- Good potential for HCCI fuel / fuel-component.
- Ethanol is a true single-stage ignition fuel.
  - May offer advantages for control & boosted oper.



# Detailed Exhaust Speciation – PRF80

- Joint project with LLNL ⇒ spec. analysis. Sandia ⇒ engine op. & data interpretation.
- Conducted fueling(ϕ)-sweep & data for near-misfire conditions. Results provide:
  - Data for aftertreatment & model validation.
  - Improved understanding of combst. process.
- PRF80 is a 2-stage ignition fuel at conditions studied. ⇒ Affects emissions compared to iso-octane & gasoline.
  - OHC fraction is greater for PRF80.
  - Unreacted-fuel fraction is much lower. ⇒ Cool-flame reactions incr. fuel breakdown.
- Ratio of *n*-heptane / iso-octane is 19-23%, compared to 25% in fuel.
  - *n*-Heptane breaks down more readily, but it induces substantial iso-octane breakdown.
- Relatively high conc. of *n*-Heptene & Phenol ⇒ former due to *n*-Heptane reactions.



# Future Work

- Complete investigation of intake boost for extending the high-load limit of gasoline-fueled HCCI at a representative speed, 1200 rpm (FY09).
- (FY10) Expand boost study to include a range of higher engine speeds, boost levels, and back-pressures for realistic turbo-charger efficiencies.
  - Two-stage fuels to be done as part of Chevron-funded project.
- Extend TS study: 1) improve diagnostic S/N & optical setup, 2) investigate methods of increasing TS, and 3) determine cause of flows producing TS.
  - Collaborate with J. Oefelein to apply LES modeling $\Rightarrow$ mechanism / enhancement.
- Additional ethanol studies over a wide range of operating parameters: EGR, load, & boost to high levels $\Rightarrow$ with M. Sjöberg, Adv. SI-Fuels Lab.
- Complete exhaust-speciation analysis for 2-stage ignition fuel, PRF80, and compare with single-stage ignition fuels, gasoline and iso-oct. $\Rightarrow$ with LLNL.
  - Analyze emiss. species for near misfire with single- and two-stage ignition fuels.
- Continue to collaborate with LLNL on improving chemical-kinetic mechanisms and on CFD/kinetic modeling.

# Summary

- Quantitative temperature-map images show that thermal strat. (TS) develops progressively during latter compression stroke ⇒ throughout charge.
- Data indicate that TS results from wall-heat transfer and convection.
  - Future work will focus on understanding the mechanism for bulk-gas TS, and potential methods for increasing it to increase the high-load limit of HCCI.
- EGR substantially improves boosted HCCI operation with gasoline fuel.
  - Achieved 16.3 bar $IMEP_g$, Ind. Thermal-Eff. = 47%, no Knock & no NOx or PM.
  - Near high-load limit for conventional diesel.  Shows significant potential for extending HCCI range – full time HCCI?
- Ethanol is a promising HCCI fuel.  Performance is generally similar to gasoline, but no low-temp. ("cool-flame") chemistry.
  - Possible advantages for control and for boosted op. ⇒ additional studies req'd.
- Detailed exhaust speciation of a two-stage ig. fuel (PRF80), shows significantly different behavior from single-stage fuels, iso-octane & gasoline.
  - More breakdown of fuel & fuel-like species to smaller species, higher OHC fract.