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: ACE004**

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.

Barriers

- Extend HCCI (LTC) operating range to higher loads.
- Improve the understanding of in-cylinder processes.
- Increase the efficiency of HCCI (LTC).

Budget

- Project funded by DOE/VT:
  FY09 – $700k
  FY10 – $750k

Partners / Collaborators

- Project Lead: Sandia ⇒ John E. Dec
- Part of Advanced Engine Combustion working group – 15 industrial partners
- General Motors – specific collaboration
- LLNL – 2 groups
- Stanford University
- Univ. of Michigan
- Univ. of New South Wales, Australia
- Chevron
- JBEI (Joint BioEnergy Institute)

Objectives - Relevance

<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.

FY10 Objectives ⇒ High Loads, Increased Efficiency, Improved Understanding

- Determine the impact of hot residuals on thermal stratification (TS), and investigate the differences in TS between motored and fired conditions.
  - Conducted collaboratively with Jordan Snyder & Ron Hansen, Stanford Univ.
- Initial investigation of the near-wall sources of TS and how it spreads into the bulk gas. ⇒ Side-view imaging with vertical laser sheet.
- Evaluate the potential of intake boost to extend the high-load limit of HCCI over a range of engine speeds, and determine effects on efficiency.
- Initiate LES modeling project with J. Oefelein (Sandia) to supplement TS-imaging experiments & determine mechanisms producing thermal distribution.
- Support CFD and chemical-kinetic modeling of HCCI at LLNL, the Univ. of Michigan and General Motors ⇒ provide data and analysis.

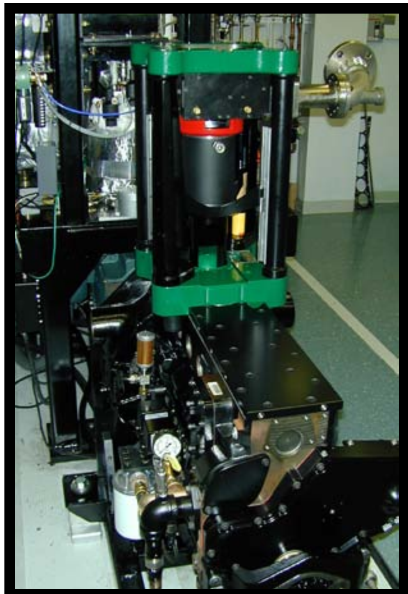
Approach

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

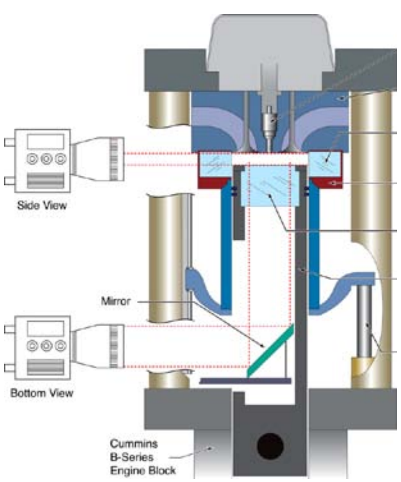
- Metal engine ⇒ conduct well-characterized experiments to isolate specific aspects of HCCI/SCCI combustion.
  - Intake boost: Select a representative boost, determine how high-load limit varies with speed. Use EGR for CA50 control to maintain low ringing (no knock).
- Optical engine ⇒ detailed investigations of in-cylinder processes.
  - Thermal stratification: Apply 1- & 2-laser temperature-imaging diagnostics to obtain T-map images in both horizontal and vertical planes.
- Computational Modeling ⇒ supplement experiments by showing cause-and-effect relationships that are not easily measured. Also, to improve models.
  - Collaborate w/ J. Oefelein (Sandia) on LES modeling to understand mech. of TS.
  - Support LLNL & U of Mich. to improve kinetic mechanisms & on CFD modeling.
- Combination of techniques provides a more complete understanding.
- Transfer results to industry: 1) physical understanding, 2) improved models, 3) data to GM to support their in-house modeling of TS & boosted HCCI.

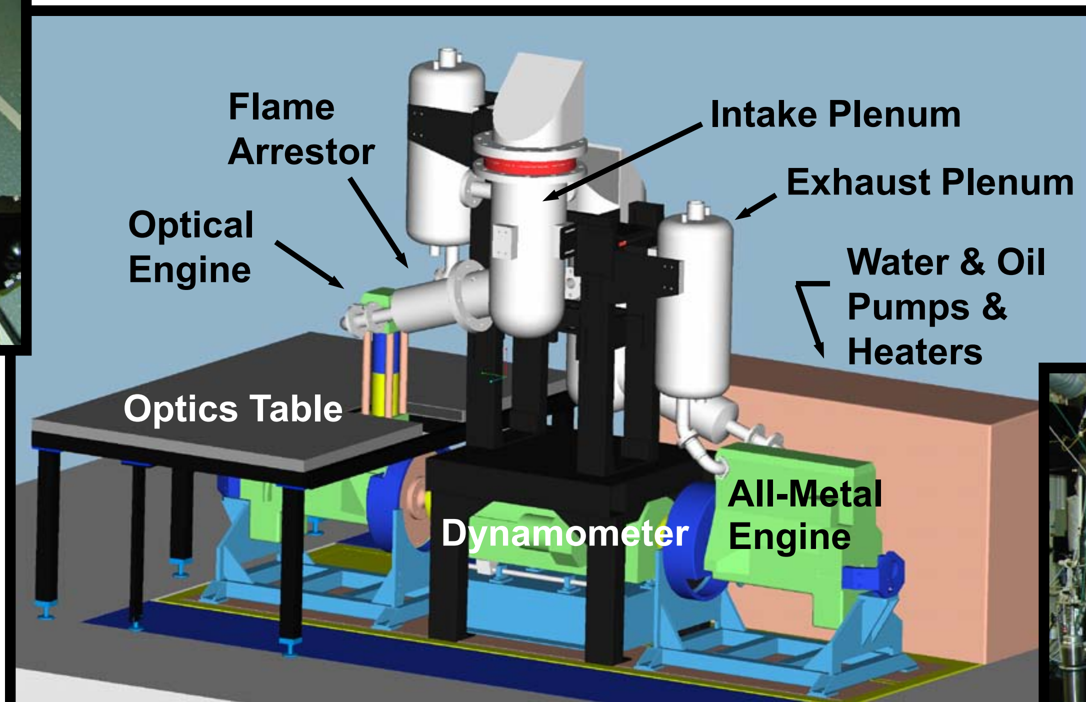
Sandia HCCI / SCCI Engine Laboratory

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

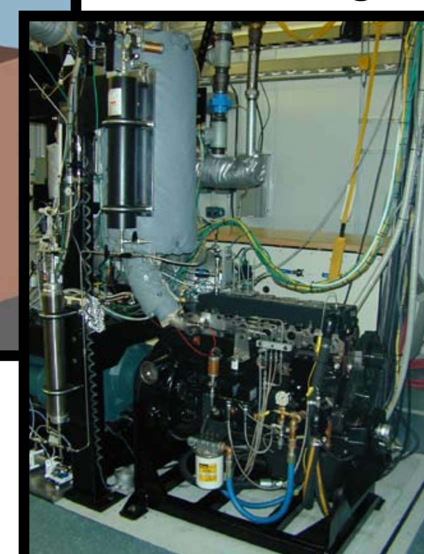


Optical Engine





All-Metal Engine



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

Accomplishments

- Determined the differences in TS between motored and fired conditions.
  - Showed that hot residuals have almost no effect on TS in a low-residual engine.
  - Compared 1- & 2-line T-imaging diags. Achieved images with precision < 5 K.

► Showed correlation between hot zones, initial combustion, & CA10 timing.

- Investigated TS distribution simultaneously in near-wall regions & bulk-gas.

► Determined why high CA50 retard (to prevent knock) is possible with boost.

- Evaluated the use of intake boost for extending the high-load limit of HCCI over a range of engine speeds.

► Initiated investigation into improving efficiency of boosted, high-load HCCI.

- Collaborating with J. Oefelein on LES modeling to supplement TS-imaging experiments with the goal of determining the mechanisms producing TS.

► Expanded investigation of ethanol-fueled HCCI, in collab. with M. Sjöberg.

- Supported chemical-kinetic and CFD modeling work at LLNL, the Univ. of Michigan and General Motors $\Rightarrow$ provided data and analysis.

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Importance of Thermal Stratification (TS)

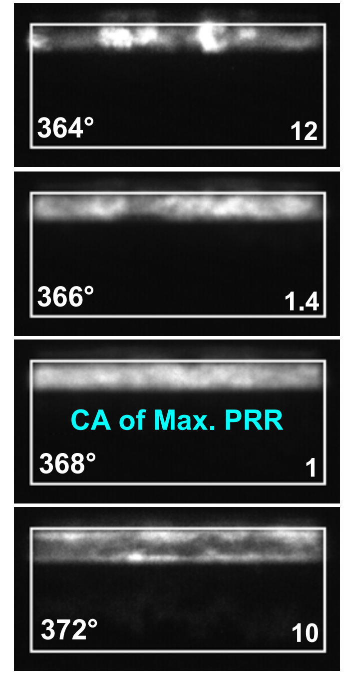
- TS causes autoignition to occur sequentially from hottest region to coldest.
  - Reduces max. pressure-rise rate (PRR).
- TS allows higher fueling without knock.
  - Also, allows more optimal combust. phasing.
- Chemilum. images show ⇒ hot reactions start intermittently near the mid-plane.
  - At time of max. PRR most combustion is from bulk gases (central region).

- TS of the <u>bulk gas</u> is critical for high-load HCCI operation.

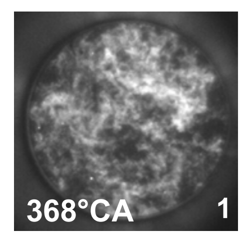
- <u>FY09</u>: Temp. images show TS development in central bulk gas, late in compression stroke.
  - Motored engine ⇒ similar prior to combustion.

- Additional knowledge of TS needed ⇒ important because of its potential for increasing the high-load limit of HCCI.

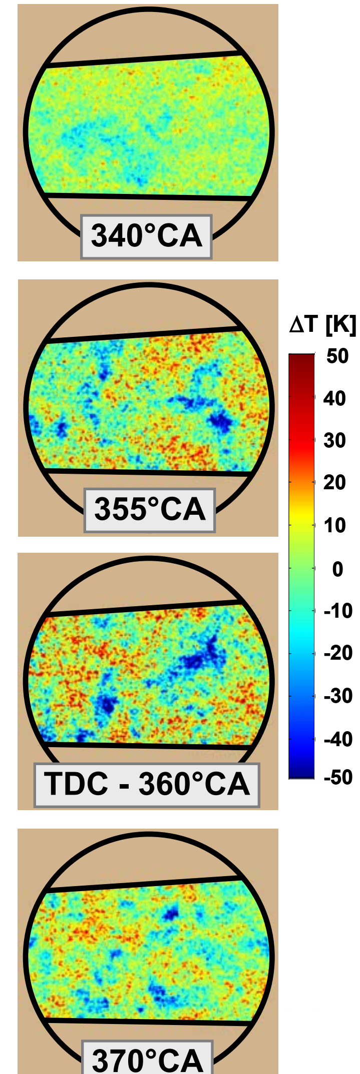
<u>Side-View</u>



<u>Bottom-View</u>

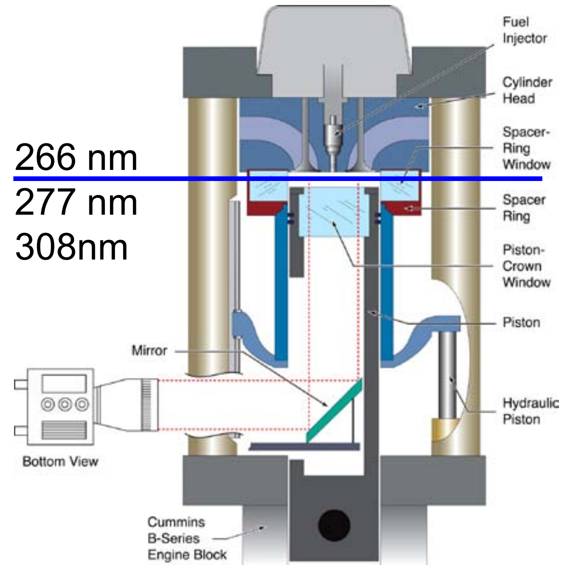


<u>T-Map Images</u>
mid-plane

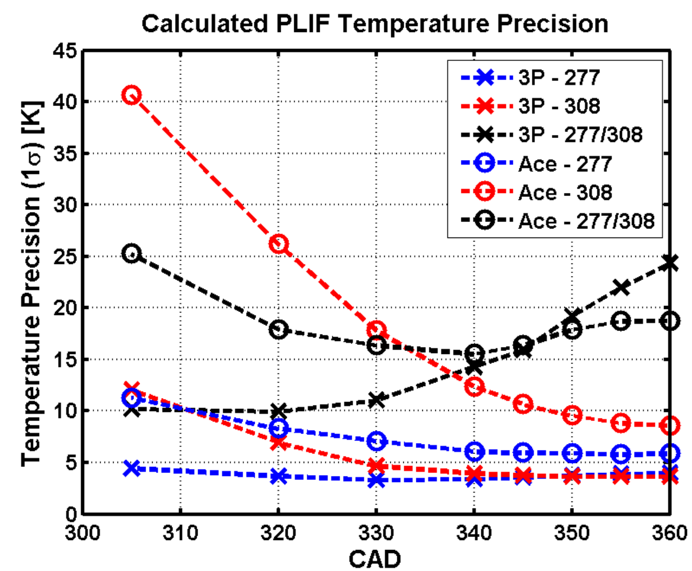


Temperature-Map Imaging Diagnostics

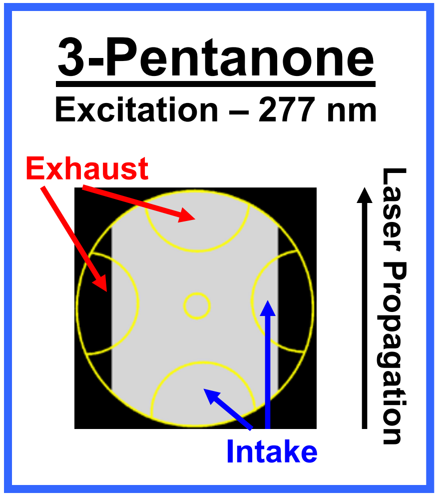
- <u>FY09 work</u>: single-line PLIF of toluene tracer.
  - Excite with Nd:YAG @ 266 nm
  - Run inert with N_2 to prevent quenching ⇒ motored
- <u>Current work</u>: one- and two-laser PLIF
  - 3-Pentanone and Acetone tracers
  - No O_2 quench ⇒ **<u>Run with N_2 (motored) or air (fired)</u>**
  - Excimer lasers 308 & 277 nm (Raman shift in H_2)
  - Two-lasers: simultaneous Temp. and composition
  - One-laser: T-maps ⇒ well mixed
- Temp. sensitivity of 1-line measurement is much better than 2-line.
  - Improved SNR
  - Improved photophysical dependence



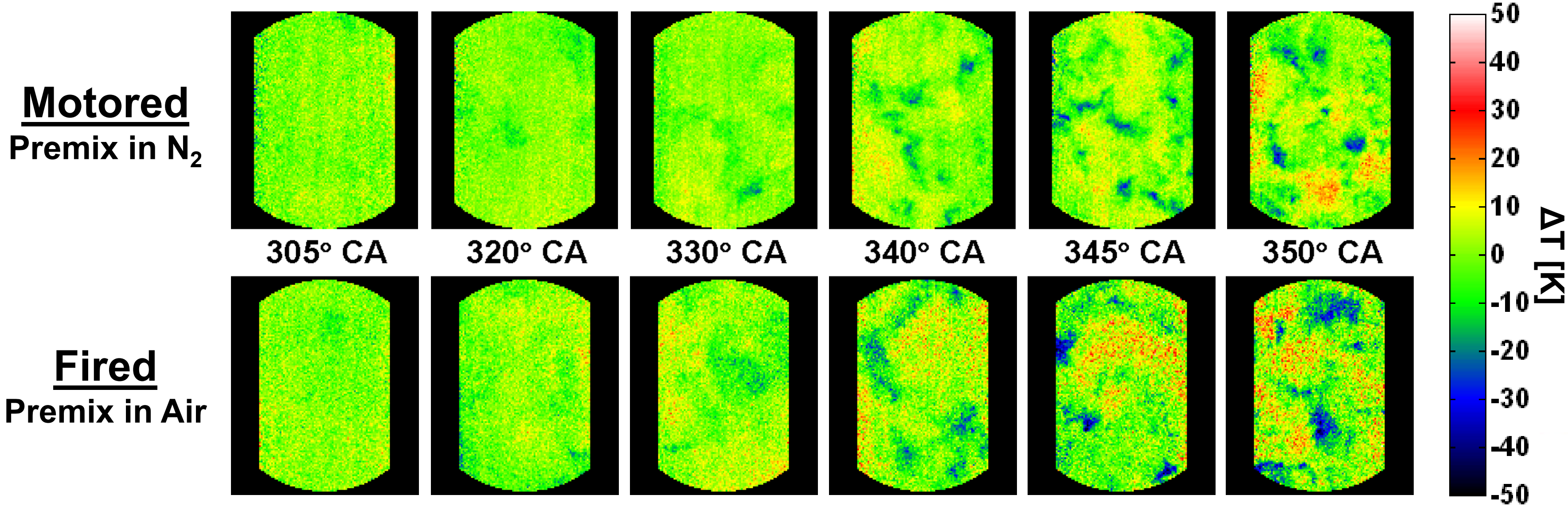
- Achieved single-shot **<u>precision below 5 K</u>** for single-line 3-Pentanone measurements.



Comparison of TS, Motored and Fired



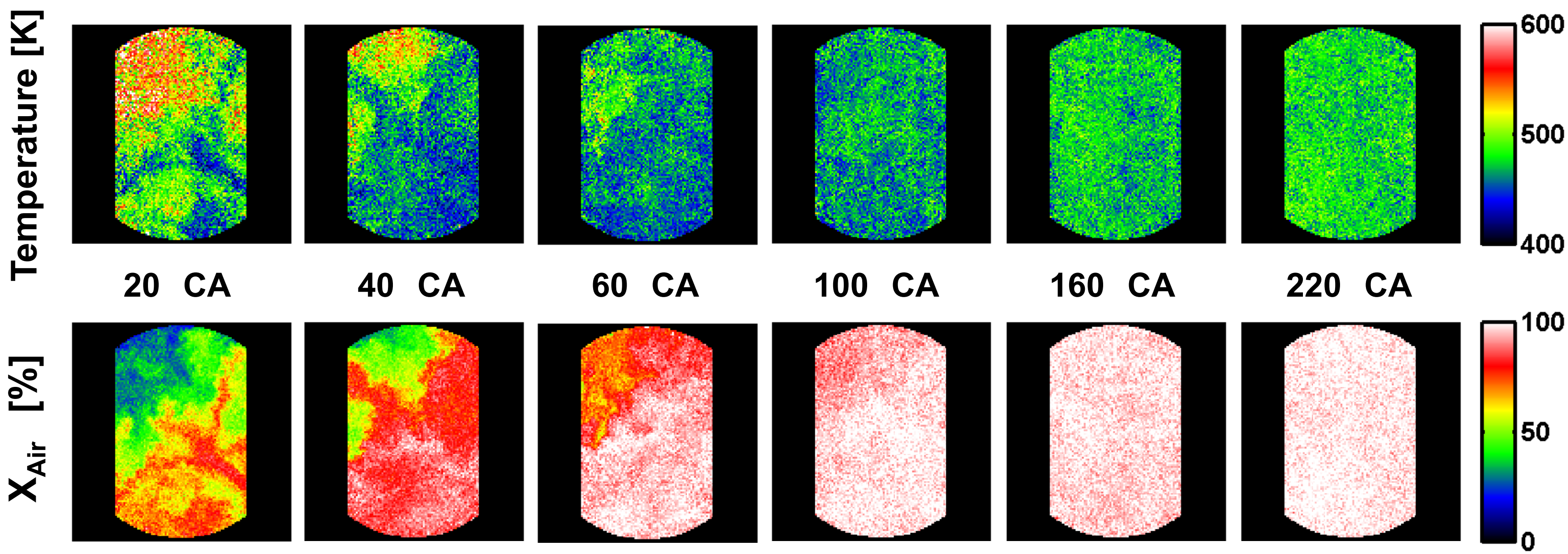
- Laser sheet at mid-plane, representative of bulk gas.
- Temperature variations & distribution at TDC agrees well with previous measurements using toluene PLIF.
- TS develops progressively during late compression stroke as cold pockets convected into central region.
- TS of motored & fired engine is similar, for matching T_{wall}
  – Indicates effect of hot residuals is small.



Residual-Mixing Evolution

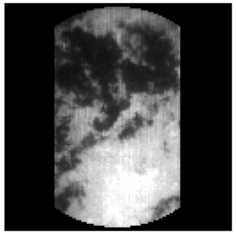
- **<u>Two-line measurements</u>** provide T and X_{air} (air mole fraction) to track mixing evolution of hot residual gas and intake air. (PLIF tracer in the air).
  - Laser sheet in mid-plane, or 20 mm below firedeck for later CA.
- Substantial T and mixture non-uniformity during early intake as fresh air mixes with hot residuals.
- Substantial mixing by 100   CA, and essentially complete by 220   CA.
  - Residual-gas fraction, 4-8% for this engine (conventional valve timing).

- Residuals not important for TS this engine ⇒ single-line measurements OK.



Combustion Correlation

Raw LIF Signal

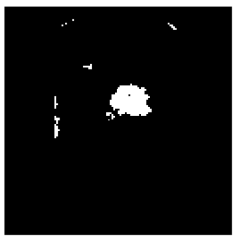


365° CA

Binarized Image

365° CA

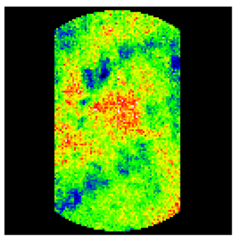
Reaction Area



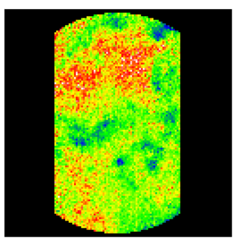
362.5° CA

365° CA

T-Map [K]

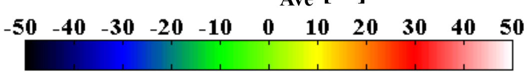


350° CA

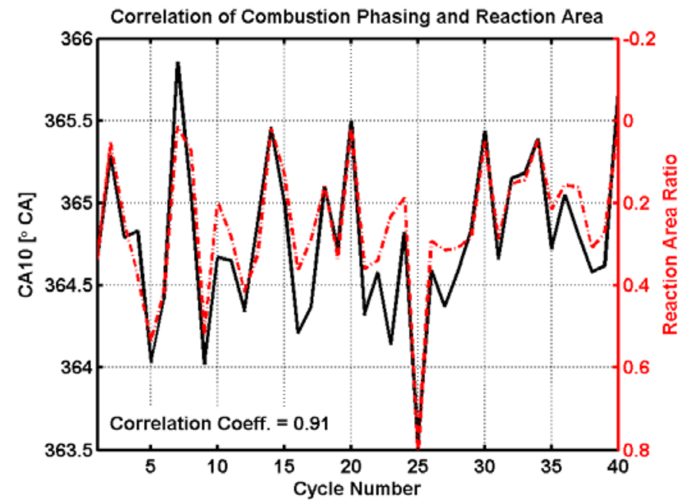


350° CA

$\Delta T = T - T_{Ave}$ [K]



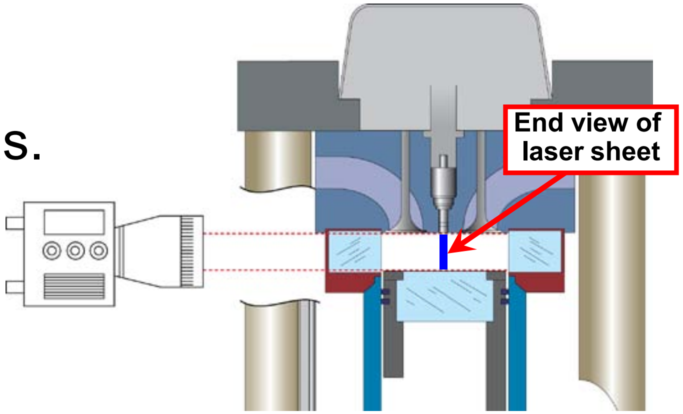
- Raw PLIF images acquired after TDC show “holes” ⇒ regions of early reaction.
  - 3-Pentanone decomposes with fuel during early HR.
  - Binarize image to show area of reacting regions.
- Early reacting regions show good correlation with high-temperature regions before TDC (350 CA).
- Excellent agreement between cycle-to-cycle variations in CA10 and the fraction of image-area showing reaction (Reaction Area Ratio) at 365 CA.



- Confirms sequential auto-ignition for HCCI comb.
- Image plane representative of main bulk-gas reactions.

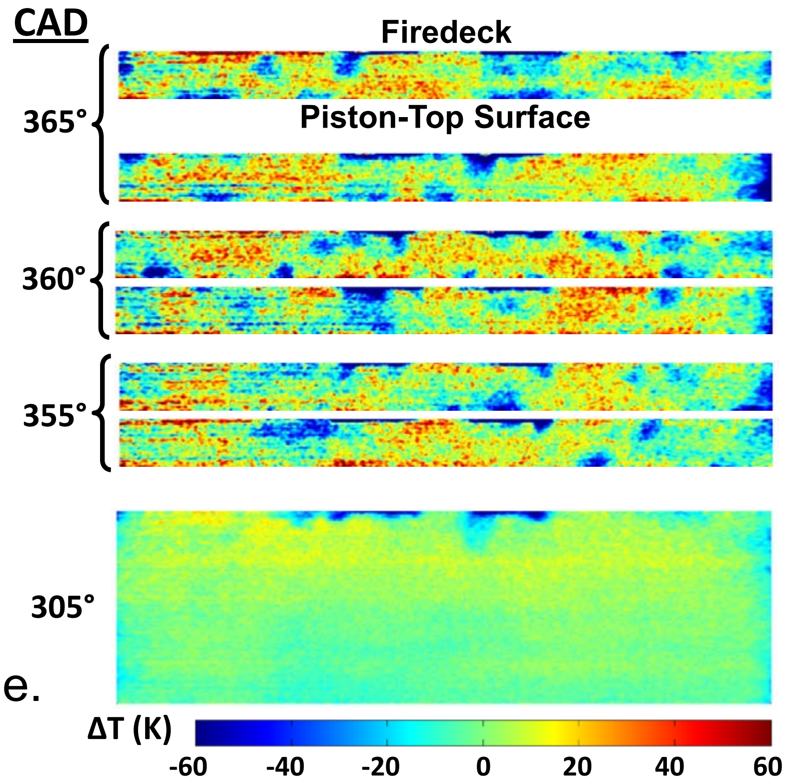
Development of TS – Side View

- Orient laser sheet vertically ⇒ image from side.
- Provides view of boundary layers (BL) & bulk gas.
  - Center plane is representative of entire volume.
- New image processing techniques required.
  - First-order correction for vignetting.



- 305 CA: Bulk-gas nearly uniform, cold pockets only along firedeck.

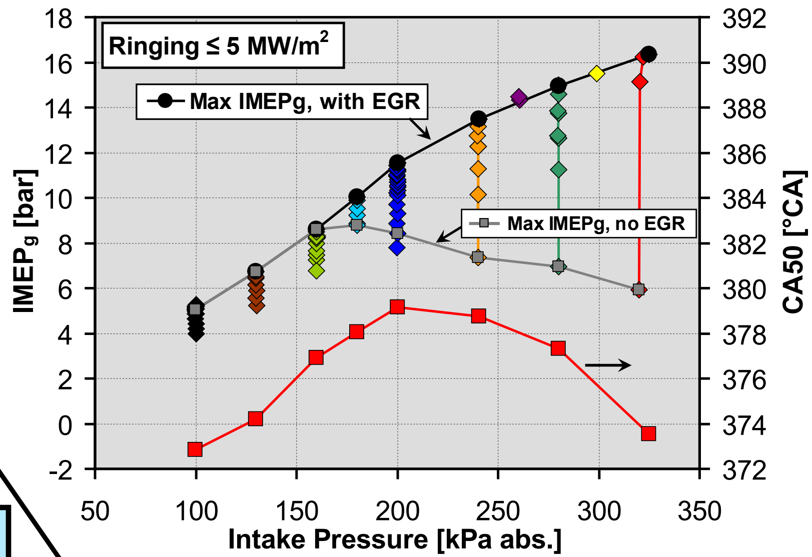
- **355 - 365 CA: Significant TS by TDC.**
  - Cold pockets present throughout bulk gas.
  - Somewhat more cold regions near walls.
  - Large size of hot regions near TDC indicates more TS is possible.



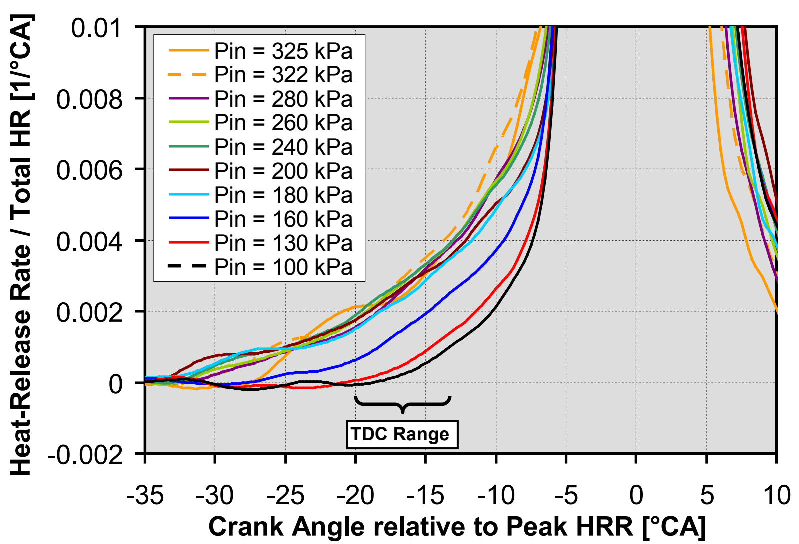
- Distribution of TS is in agreement with horizontal-plane images.
  - Side-view better ⇒ shows TS of entire volume.
  - Additional analysis is underway.

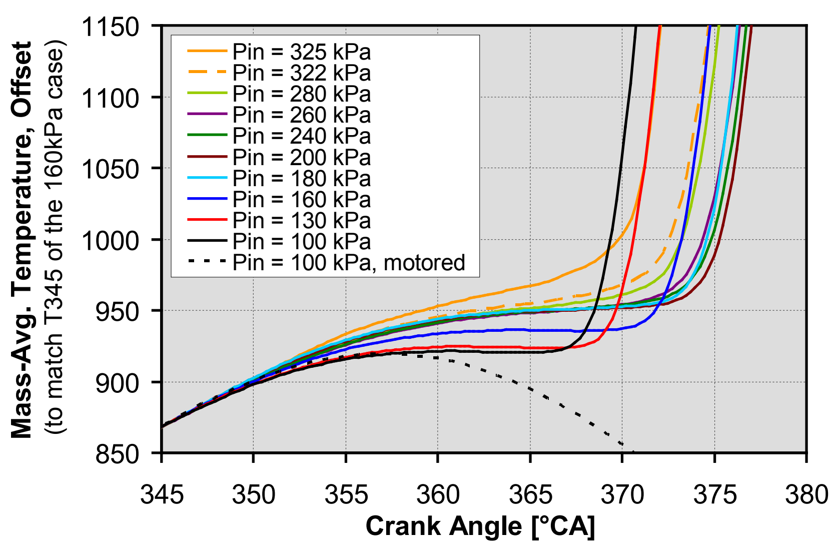
Maintaining Stability with High Retard

- Max. IMEP$_g$ increases greatly with boost, up to 16.3 bar $\Rightarrow$ Ringing $\leq$ 5 MW/m^2.
  - EGR slows autoignition to retard CA50.
- Substantial timing retard with good stability is the key to controlling knock.
- Stability depends on dT/dθ prior to onset of main comb. *Sjöberg & Dec, P. Comb. Inst. 2006*
- HRR curves show the reason is increased early ITHR with boost, for gasoline.



Details in SAE 2010-01-1086

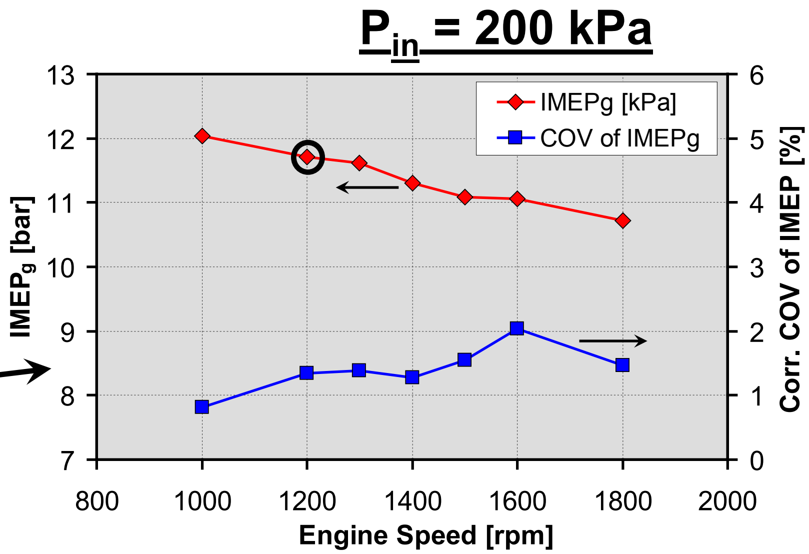


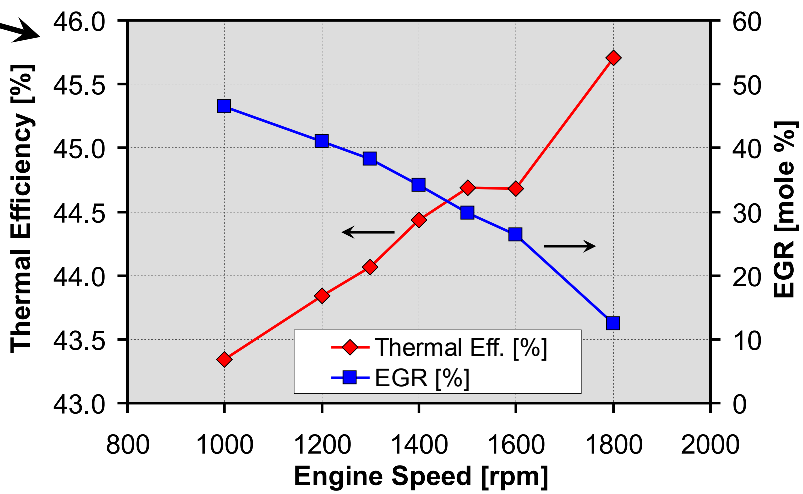


Speed Effects on Max. Load with Boost

- Boost effective for high loads at 1200 rpm.
- How does engine speed affect max. load?
  - Select P_{in} = 200 kPa as representative.
  - Determine knock/stability limit, each speed.
- Max. $IMEP_g$ decreases moderately with speed. ⇒ 12.0–10.7 bar, 1000–1800 rpm
  - Stability is good, COV of $IMEP_g \leq 2\%$.
- Thermal efficiency improves with speed.
  - Less EGR required
  - Less heat transfer
- Maintain ringing ≤ 5 MW/m^2 ⇒ no knock.

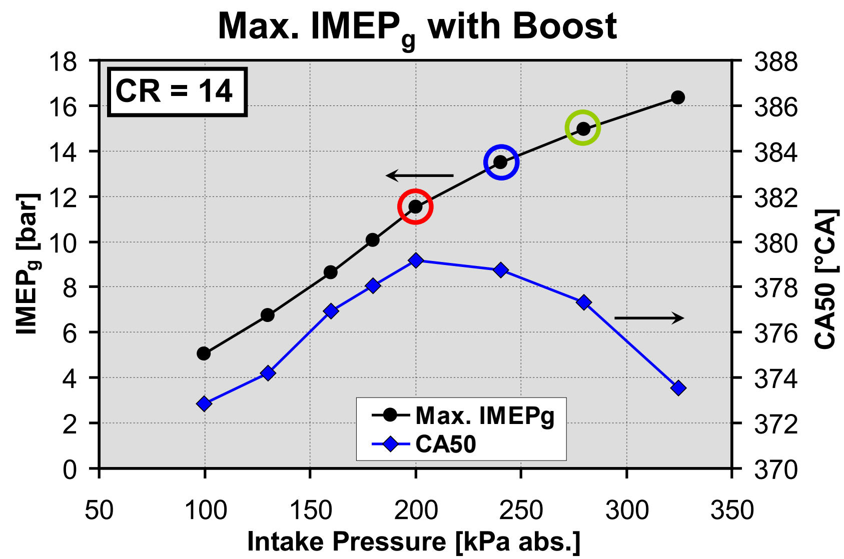
- Boosted HCCI performs well over speed range tested.



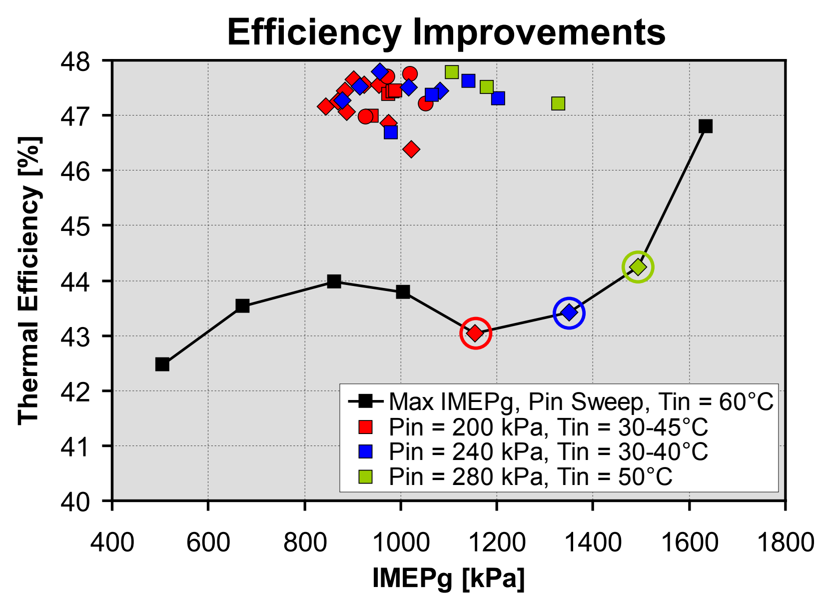


Improving Thermal Efficiency

- HCCI inherently has high-efficiency.
- Indicated thermal eff. of ~44% at high loads ⇒ straightforward.
  - Substantially better than SI engines.
- Are higher efficiencies possible?
- Examined methods to increase eff. ⇒ $R \leq 5$, & maintain relatively high IMEP.
  - Eff. improves with: less retard, less EGR, reduced T_{in}, and lower F/C mass-ratio.



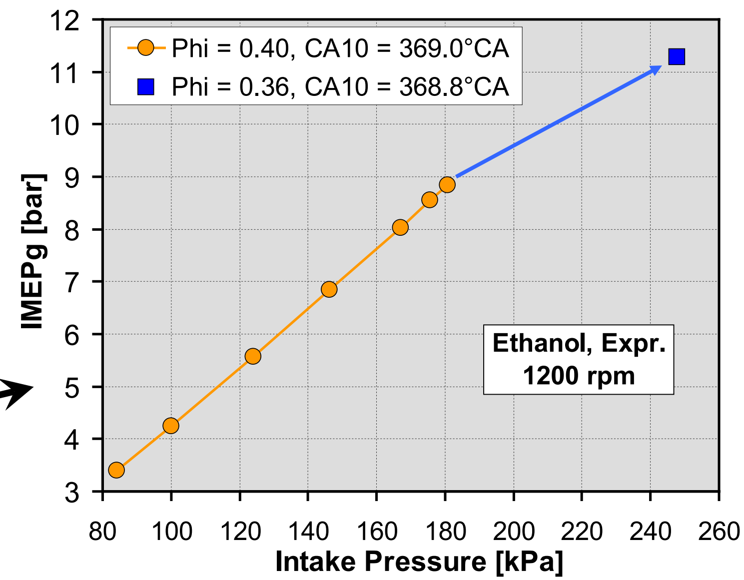
- Efficiency increased to 47 – 48 % at three boost levels examined.
  - Reduce ISFC ~9% with only modest reduction in $IMEP_g$, ~10%.



- Further gains should be possible with:
  1) Higher ON fuel ⇒ less EGR
  2) Miller cycle ⇒ greater expansion ratio
  3) Heavy-Duty engine ⇒ less heat losses

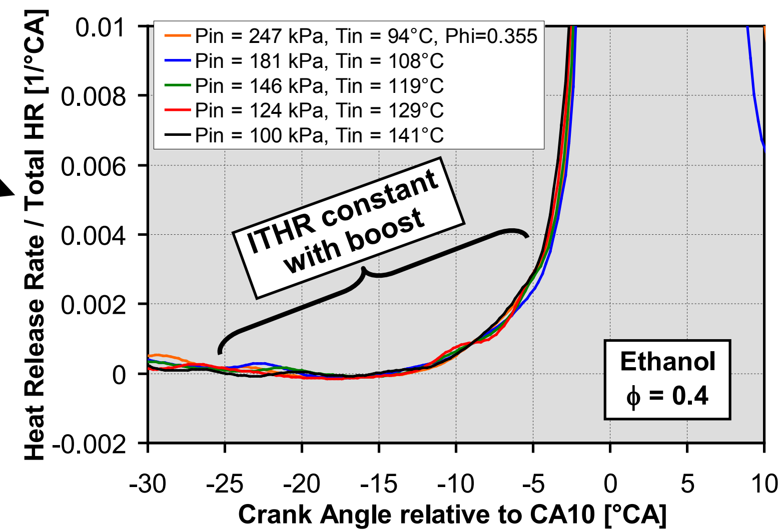
Ethanol-Fueled HCCI

- Ethanol is an important gasoline constituent and potential alternative fuel.
- Determined several aspects of ethanol's performance as an HCCI fuel.
  1) Sensitivity of CA50 to T_{in}
  2) Effects of CA50 on PRR & stability
  3) Effects of EGR on CA50
  4) Intake boosting up to P_{in} = 247 kPa.
- $IMEP_g$ increases linearly with boost to P_{in} = 180 kPa.



- For higher P_{in}, cannot retard CA50 sufficiently with good stability ⇒ reduce ϕ.

- Reason: ITHR is <u>not</u> enhanced with boost, which limits stability for retarded CA50.
  – Max. load w/ boost likely less than gasoline.

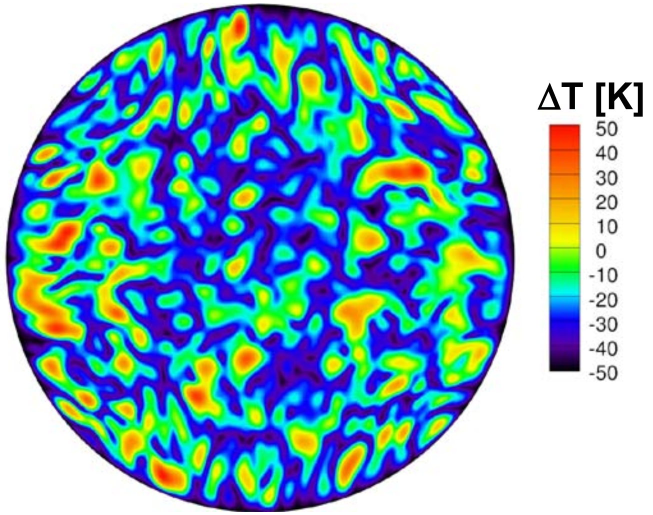


- Potential for blending w/ gasoline to reduce EGR required with boost ⇒ higher Eff.

Collaborative LES Modeling of TS

- Obtained intake-port and combustion-chamber geometry files to construct LES grid.
- Initial Large-Eddy Simulation (LES) results.
  - 3-million cell grid
  - Computations required about 2 days on Sandia cluster ⇒ using 64 processers.

Computational Domain



LES Temperature Distribution

- Temperature-map of mid-plane at TDC shows significant TS.
  - Range of ΔT matches experimental images.
  - Scale of hot/cold pockets appears finer.
  - Lack of anti-swirl plate in grid may be affecting results ⇒ will include in future runs.

- Initial LES results are very promising.
- More results by J. Oefelein later today.

Collaborations

- Project is conducted in close cooperation with U.S. Industry through the Advanced Engine Combustion (AEC) / HCCI Working Group.
  - Ten OEMs, Five energy companies, Four national labs, & Several universities.
- LLNL: 1) Support chemical-kinetic mechanism development, Pitz *et al*.
  2) Support CFD modeling work of Aceves *et al.*
- SNL: 1) Collaborative project on LES modeling of HCCI, Oefelein *et al.*
  2) Collaborate on ethanol HCCI with SI alt.-fuels lab, Sjöberg *et al.*
- General Motors: Bi-monthly internet meetings ⇒ in-depth discussions.
  - Support GM modeling of boosted HCCI and thermal strat. with data & discussions.
- Stanford Univ: Collaborate on development of Temperature-Imaging diagnostics for HCCI ⇒ hosted Ph.D. student J. Snyder for 6 months.
- U. of Michigan, and U. of New South Wales: Support modeling with data.
- Chevron: **Funds-In project** on advanced petroleum-based fuels for HCCI.
- JBEI (Joint BioEnergy Institute): **Funds-In project** on 2nd generation biofuels for HCCI ⇒ current studies involve iso-pentanol.

Future Work

Thermal Stratification

- Complete side-view imaging study of evolution of TS from BL to bulk-gas.
- Extend TS study: 1) Determine cause of flows producing the TS, 2) Speed effects on TS, and 3) Investigate methods of increasing TS.
- Continue/expand collaboration with J. Oefelein *et al.* on use of LES modeling to understand mechanisms of TS and how to enhance them.

High-Efficiency, Boosted HCCI

- Extend investigation of boosted HCCI to even higher speeds.
- Explore additional methods for increasing thermal efficiency of boosted HCCI $\Rightarrow$ Fuel effects, Operating conditions, Miller cycle.
- Spark-assisted HCCI.

Support of HCCI Modeling

- Continue collaborations with GM-research on HCCI modeling.
- Continue to collaborate with LLNL on improving chemical-kinetic mechanisms and on CFD/kinetic modeling.

Summary

- Showed that development of thermal strat. (TS) in a fired engine is nearly identical to that of a motored engine, up to onset of ignition.
  - Residuals are well-mixed by BDC-intake ⇒ little effect on TS (low-resid. engine).
- Hottest regions 10 bTDC correlate well with first-burned regions & CA10.
- Developed side-view imaging to simultaneously image boundary-layer and bulk-gas TS ⇒ insights into spread of TS from wall-regions to bulk-gas.
  - Large size of hot regions near TDC indicates significantly more TS is possible.
- Boost enhances the intermediate temp. HR (ITHR) of gasoline allowing substantial CA50 retard with good stability ⇒ the mechanism that allows high-load, boosted HCCI with no knock.
- Boost is effective for achieving high-load HCCI across a range of speeds.
- Efficiency of boosted HCCI has been increased to 47– 48% for 8–13 bar $IMEP_g$.
- Initial results show LES modeling has good potential for providing the understanding required to develop methods of enhancing the TS to extend the high-load limit of HCCI.
- Determined several aspects of ethanol's performance as an HCCI fuel.