HCCI and Stratified-Charge CI Engine Combustion Research

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May 10, 2011 – 9:30 a.m.

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

Program Manager: Gurpreet Singh **Project ID: ACE004**

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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.
- Increase the efficiency of HCCI (LTC).
- Improve the understanding of in-cylinder processes.

Budget

- Project funded by DOE/VT:
  FY10 – $750k
  FY11 – $750k

Partners / Collaborators

- Project Lead: Sandia ⇒ John E. Dec
- Part of Advanced Engine Combustion working group – 15 industrial partners
- General Motors – specific collaboration
- LLNL – support kinetic modeling
- Univ. of Michigan
- Univ. of New South Wales, Australia
- Chevron
- LDRD – advanced biofuels project (internal Sandia funding)

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 or HCCI-like engines by industry.

FY11 Objectives ⇒ High Loads, Increased Efficiency, Improved Understanding

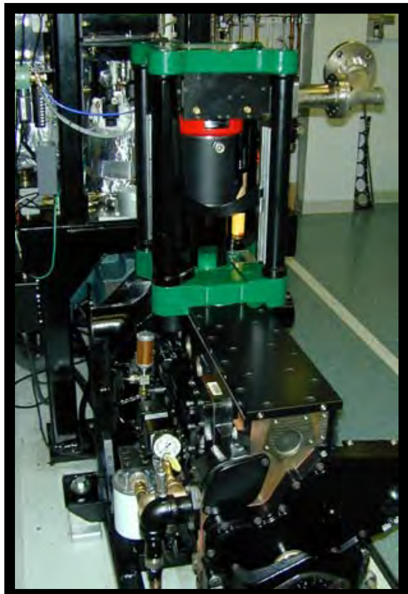
- <u>Thermal Stratification (TS)</u>: Determine 1) the main sources of colder near-wall gases, and 2) the primary mechanisms for transport and dispersion of this colder gas into the hotter bulk gas, at a base operating condition.
  - Initiate investigation of how operating conditions affect the development of TS.
  - Improve PLIF-based thermal imaging technique for side-view imaging.
- <u>Improved Efficiency of Boosted HCCI</u>: Examine various operating techniques to determine their potential for increasing the efficiency of intake-boosted HCCI (*e.g.* effects of T_{in}, CA50, ringing, DI vs. pre-mixed fueling).
- Continue collaborations with J. Oefelein (Sandia) to conduct LES modeling to better understand the mechanisms producing TS & how to improve TS.
- Support chemical-kinetic and CFD modeling of HCCI at LLNL, the Univ. of Michigan and General Motors ⇒ provide data and analysis.

Approach

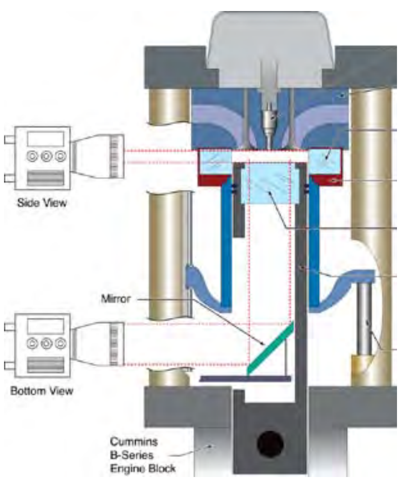
- Use a combination of metal- and optical-engine experiments and modeling to build a comprehensive understanding of HCCI processes.

- Metal engine ⇒ conduct well-characterized experiments to isolate specific aspects of HCCI/SCCI combustion.
  - Improved efficiency: Select representative boost, determine effect of parameters of interest (T_{in}, CA50, fueling method) while holding other key parameters const.
- Optical engine ⇒ detailed investigations of in-cylinder processes.
  - Thermal stratification: Apply PLIF-based thermal-imaging using a vertical laser sheet to simultaneously image both the boundary layer (BL) and bulk gas.
- 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.

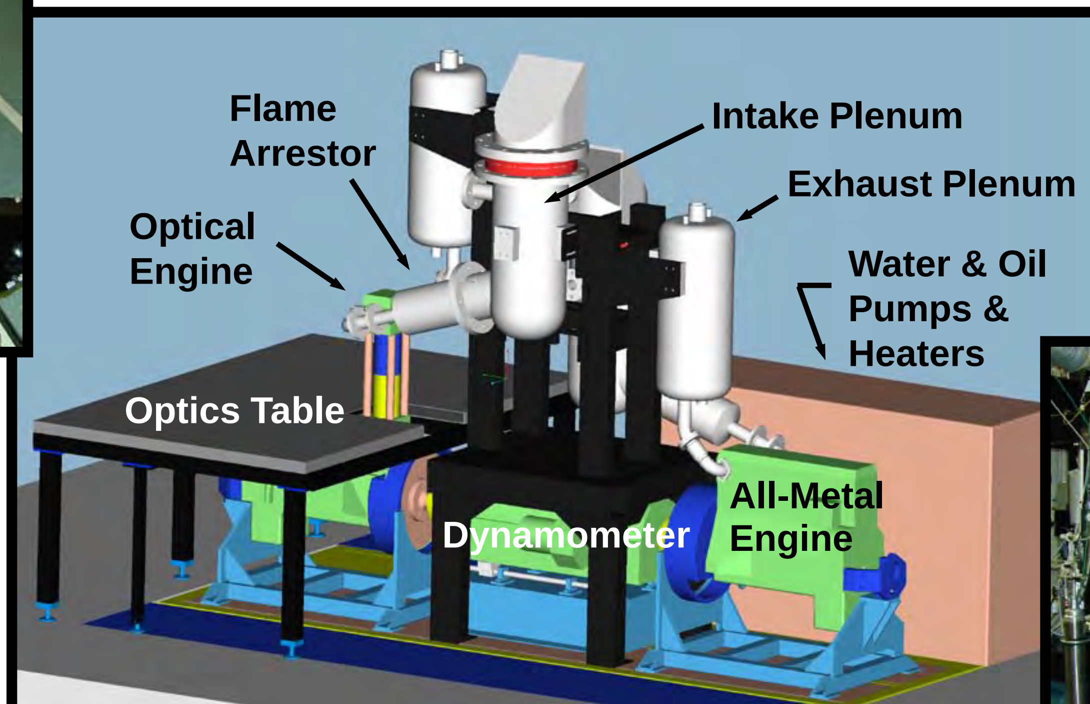
Sandia HCCI / SCCI Engine Laboratory



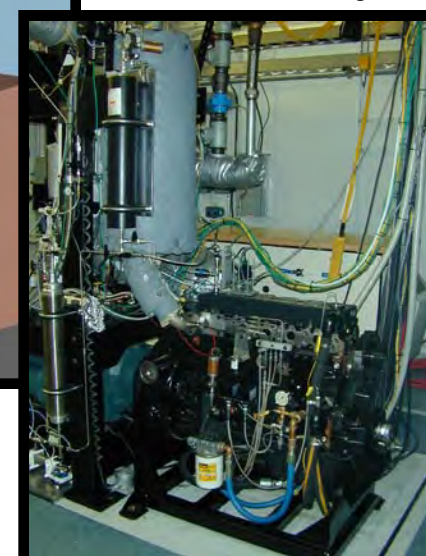
Optical Engine



- 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

Metal-engine experiments ⇒ Fuel is gasoline: RON = 91.7, MON = 83.4

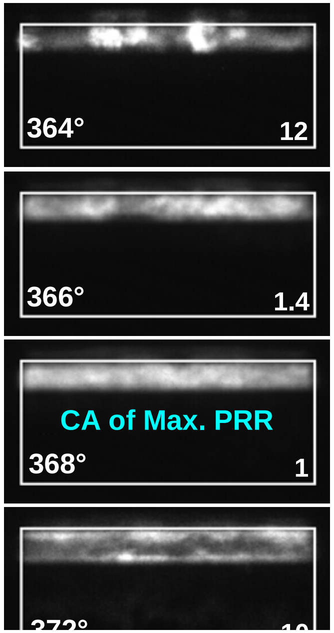
Accomplishments

- Determined the main sources of colder near-wall gases and the mechanism for dispersing this colder gas into the hotter bulk-gas to produce TS.
  - Significantly improved side-view thermal imaging technique.
  - Preliminary data for effect of operating parameters on development of TS.
- Evaluated effects of fueling method on efficiency: premixed, DI, & Partial-DI.
  - Showed significant efficiency improvements with DI & partial-DI for boosted HCCI.
- ► Showed that partial-DI fueling allows a substantial increase in the high-load limit of boosted HCCI $\Rightarrow$ gasoline becomes ϕ-sensitive with boost.
- Evaluated the effects of intake temperature (T_{in}), combustion timing (CA50), and ringing-intensity on engine efficiency.
- ► Investigated benefits of partial-DI fueling with ethanol, collab. with M. Sjöberg.
- Collaborating with J. Oefelein on LES modeling to supplement TS-imaging experiments $\Rightarrow$ developed new high-fidelity grid, computations underway.
- Supported chemical-kinetic and CFD modeling work at LLNL, the Univ. of Michigan and General Motors $\Rightarrow$ provided data and analysis.

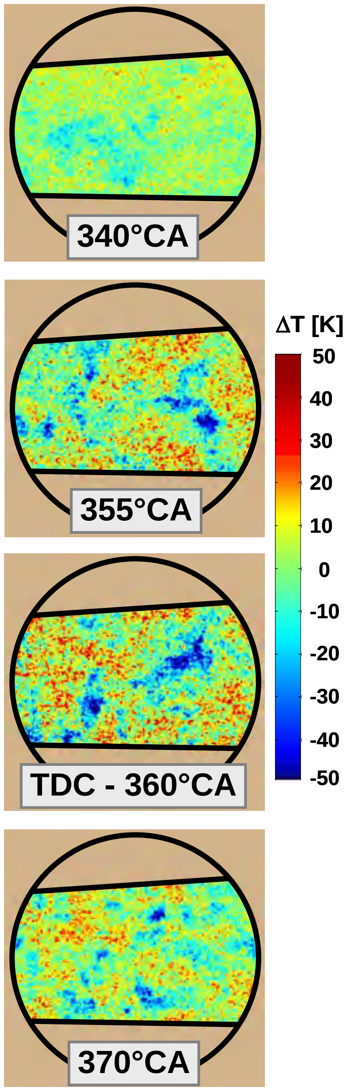
Importance of Thermal Stratification (TS)

- TS causes autoignition to occur sequentially from hottest region to coldest.
  - Reduces max. pressure-rise rate (PRR) ⇒ allows higher loads and better efficiency.
- At time of max. PRR most combustion is from bulk gases (central region).
- TS of <u>bulk gas</u> is critical for high-load HCCI.
- Prev. T-map images show TS development in bulk gas, late in compression stroke.

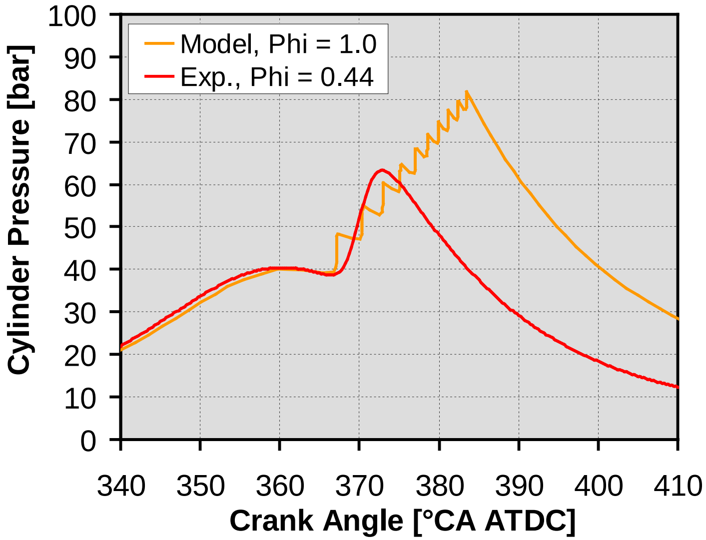
Side-View



T-Map Images
mid-plane

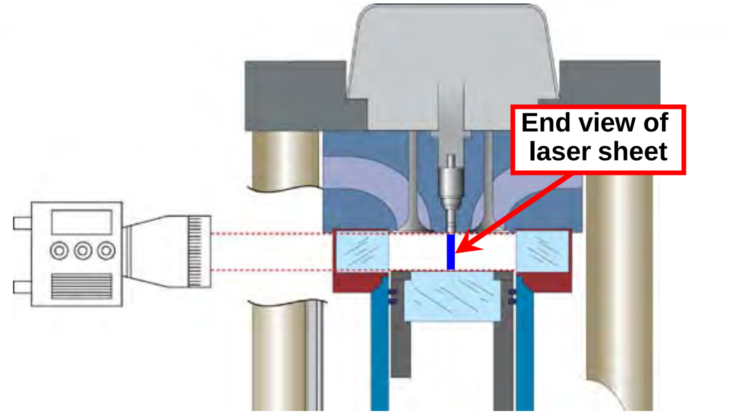


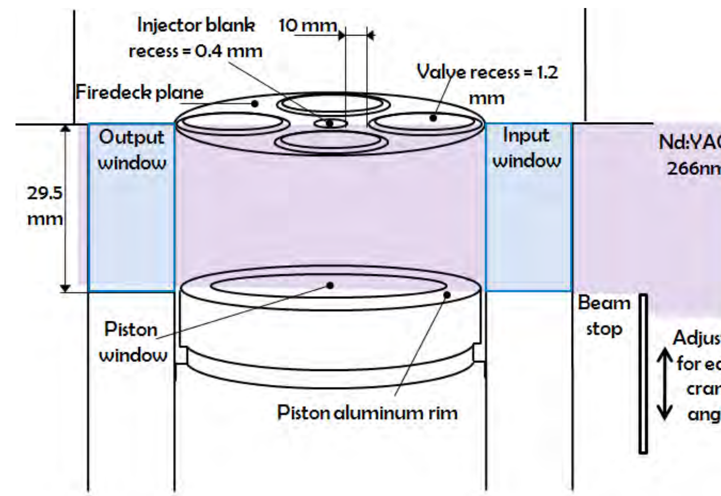
- Increasing TS has strong potential for extending the high-load limit of HCCI.
  - And/or increasing efficiency.
- A better understanding of the mechanism(s) producing TS is needed.



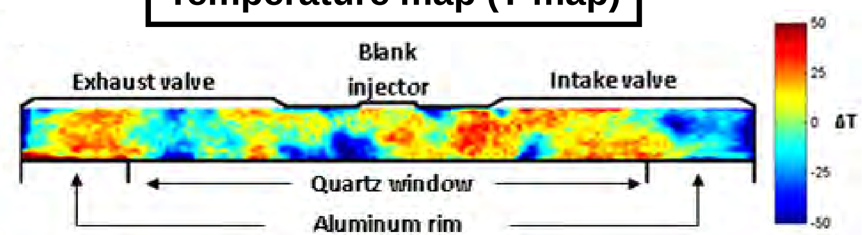
Simultaneous Bulk-Gas and BL Imaging

- T-maps from PLIF with toluene tracer.
  - Excite with Nd:YAG @ 266 nm.
  - Run inert with N_2 to prevent quenching.
  - FY10 $\Rightarrow$ motored or fired gives same TS.
  - Calibrate in-situ by varying T_{in}.
- Optical setup allows visualization of bulk-gas and boundary-layer regions.
  - View extends to cylinder wall because window acts as a divergent lens.
- Image post-processing into T-map significantly more challenging.
  - Repeatable cold BL & fluctuating temp.
  - Vignetting and beam steering.

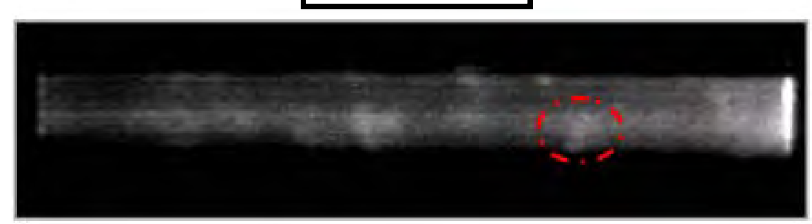




Temperature map (T-map)



Raw Image



Cycle-Averaged T-maps

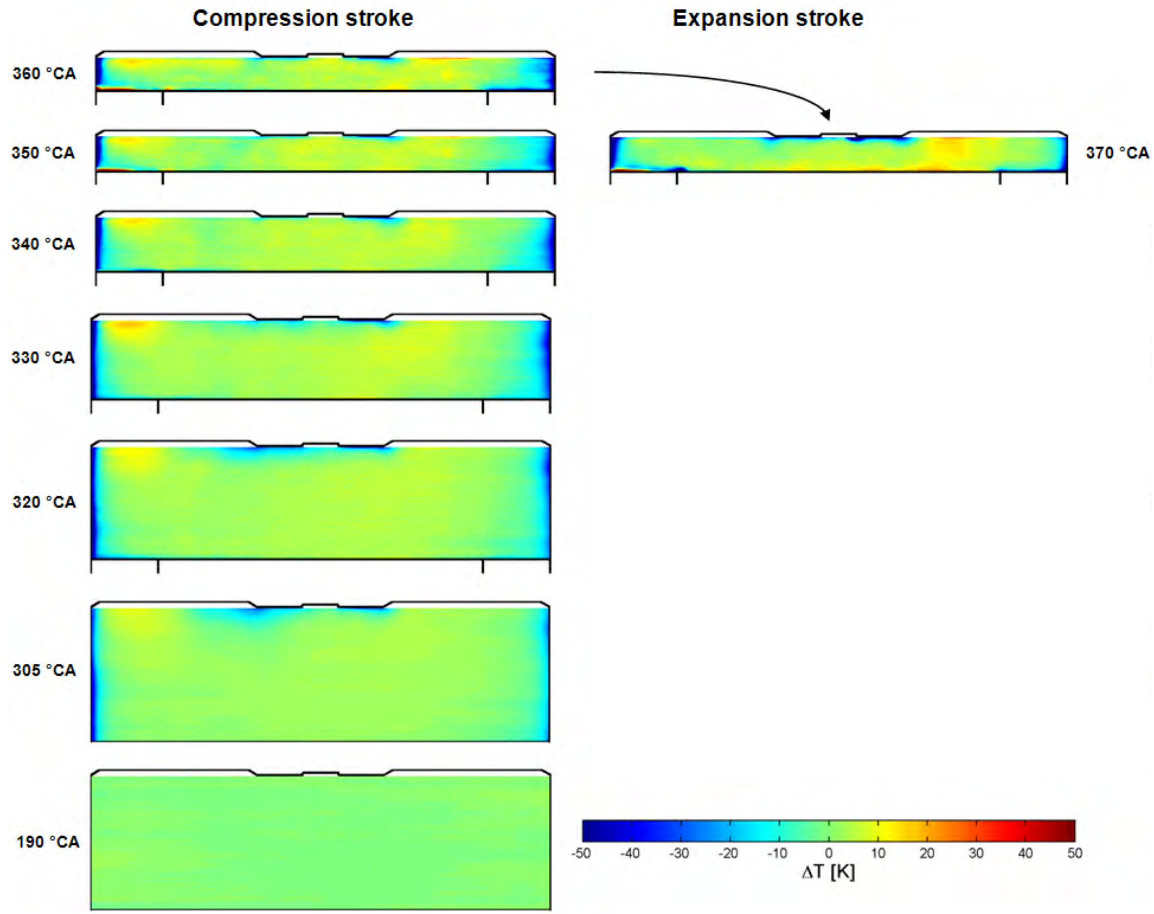
- Average T-maps show TS that is consistent from cycle to cycle.
  - Boundary layers (BL) and out-gassing during early expansion.

Compression Stroke

- Boundary layers develop at cyl. walls and firedeck.
  - Compression suppresses thickness of BL at firedeck.
- Avg. temperature is fairly uniform throughout bulk-gas.

Expansion Stroke

- BL expansion and crevice out-gassing increase TS.
  - Not relevant to controlling max. PRR.

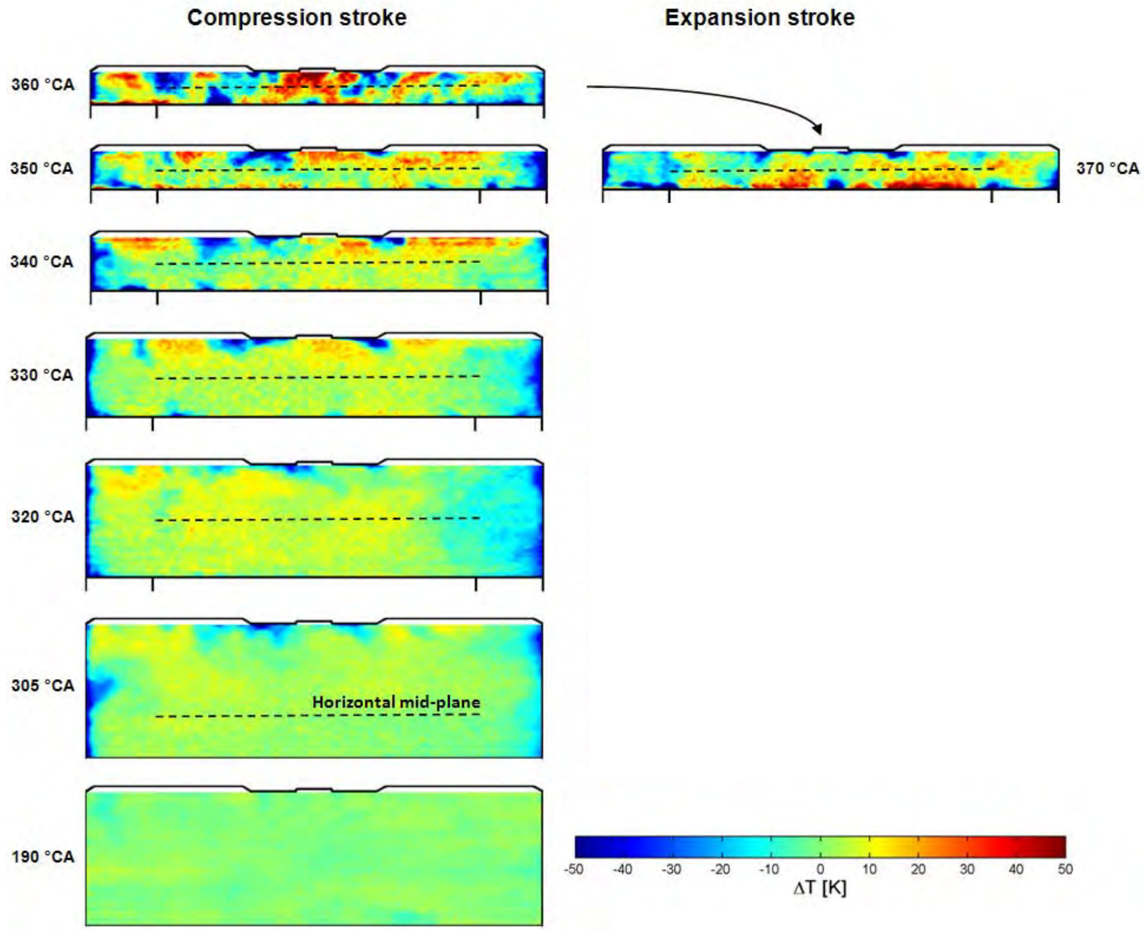


- There is no evidence of consistent flows that transport cold gas from near-wall regions into central bulk gas.

Single-Cycle T-maps

- Show all TS ⇒ 1) random fluctuations, and 2) consistent from cycle to cycle.
  – Selected images show typical amounts of TS.

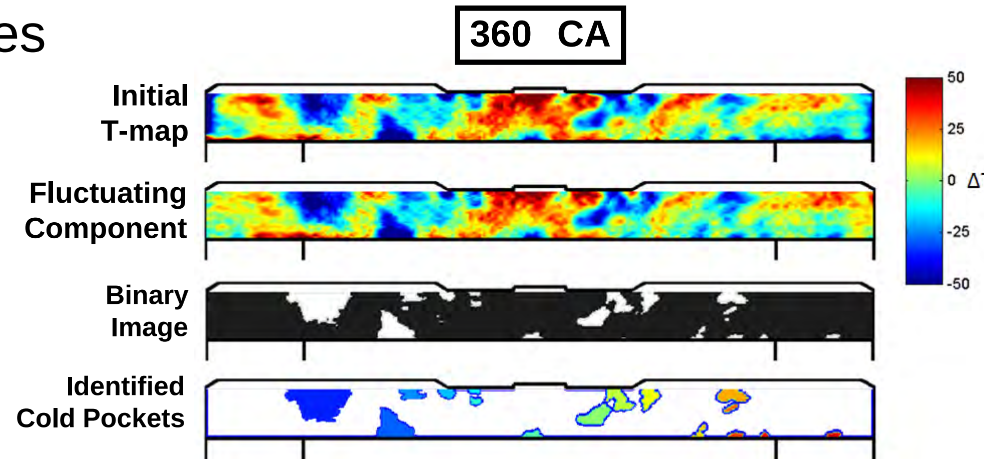
- Substantial TS is evident in the bulk gas near TDC.
- Bulk-gas TS is dominated by a randomly fluctuating pattern of cold pockets.
- Random nature suggests it results from in-cylinder turbulence.
- Characterized by turbulent structures of cold gas extending from the walls.
  – Not isolated cold pockets.

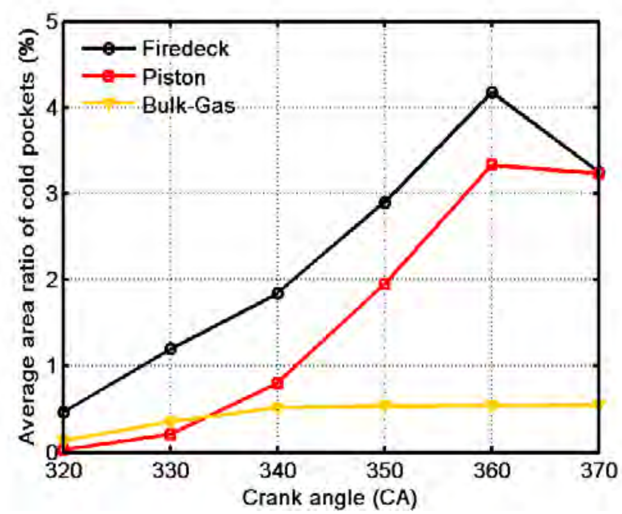


- Bulk-gas TS ⇒ critical for controlling max. PRR ⇒ appears to result from in-cylinder turbulence ⇒ turbulent structures extending from the wall.

Analysis of Cold-Pocket Structures

- Statistical analysis of turbulent cold pockets shows size and location.
- T-maps converted to binary images of cold pockets.
- Pockets categorized as:
  - attached <u>firedeck</u>
  - attached to <u>piston</u> top
  - unattached, in <u>bulk-gas</u>
- Number of cold pockets and their fraction of the total image area increase up through TDC.
- Less cold area at piston top may be related to high T of quartz piston top.

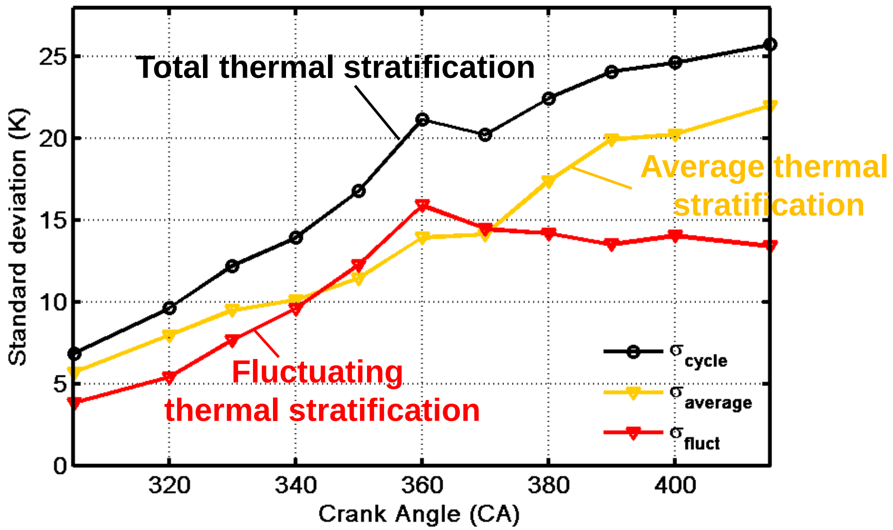




- Most cold pockets are structures attached to firedeck or piston top.
  - “Unattached bulk-gas” pockets may be attached out of image plane.

Magnitude of TS

- Std-Dev. of T-map provides quantitative measure of TS.
  - Corrected for shot noise (<1.5 K).



- Total TS increases continuously.
  - Average TS increases due to BL development & out-gassing after TDC.

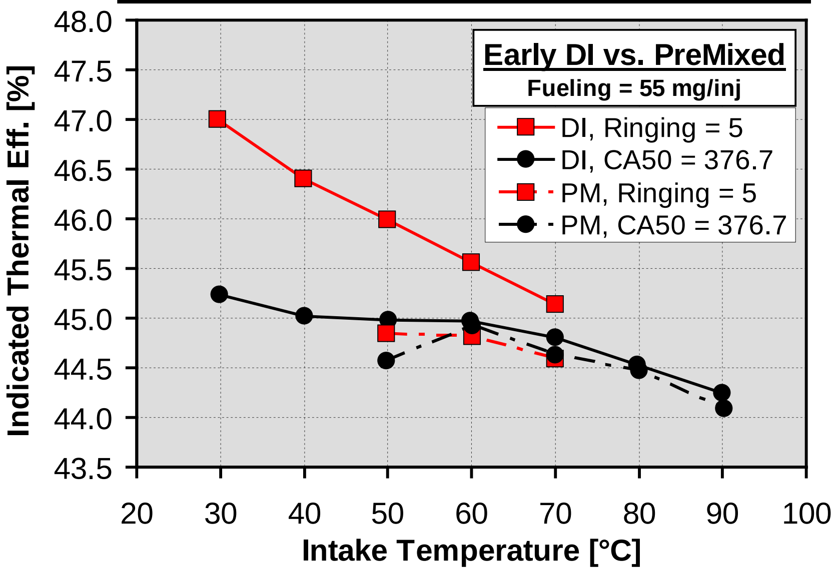
- Fluctuating component of TS reaches a maximum at TDC.
  - In agreement with SAE 2009-01-0650.

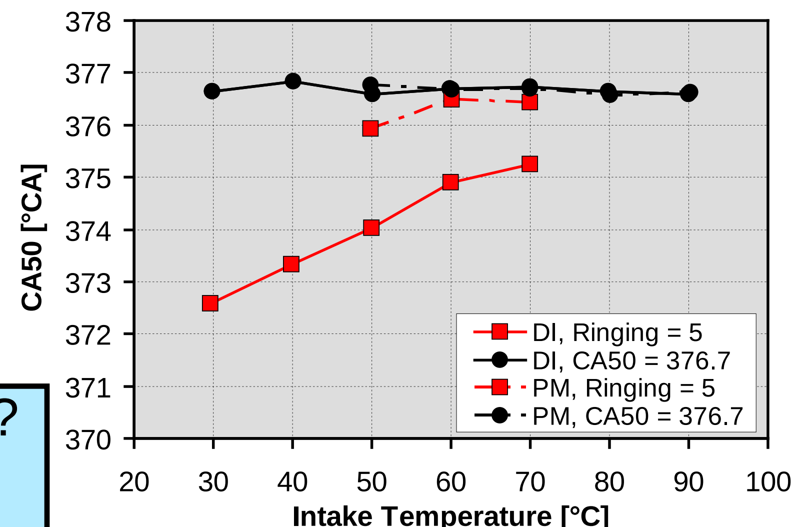
- Max. std-dev at TDC ≈ 16 K ⇒ Agrees with values required for multi-zone modeling of metal-engine burn duration (SAE 2005-01-0113).

Improving Efficiency of Boosted HCCI

- <u>FY10</u>: Showed Thermal-Eff. (T-E) could increase from 43.5 → 47.5% by adjusting various operating parameters.
- <u>FY11</u>: Conduct systematic sweeps to determine mechanisms and trade-offs.
- <u>Example</u>: Vary T_{in} with constant fueling.
  1. Const. CA50 ⇒ T-E up as T_{in} reduced.
     > Higher γ and less heat-transfer loss.
     > No advantage of DI fueling over PM.
  2. Const. Ringing = 5 MW/m^2 (const. PRR).
     ⇒ <u>PM fueling</u>: T-E similar to const. CA50 since is ringing similar.
     ⇒ <u>Early-DI fueling</u>: T-E much higher.
     > DI reduces HRR, so can advance CA50 to get ringing = 5 ⇒ higher T-E.

P_{in} = 2 bar, Fuel = 55 mg/inj, Gasoline

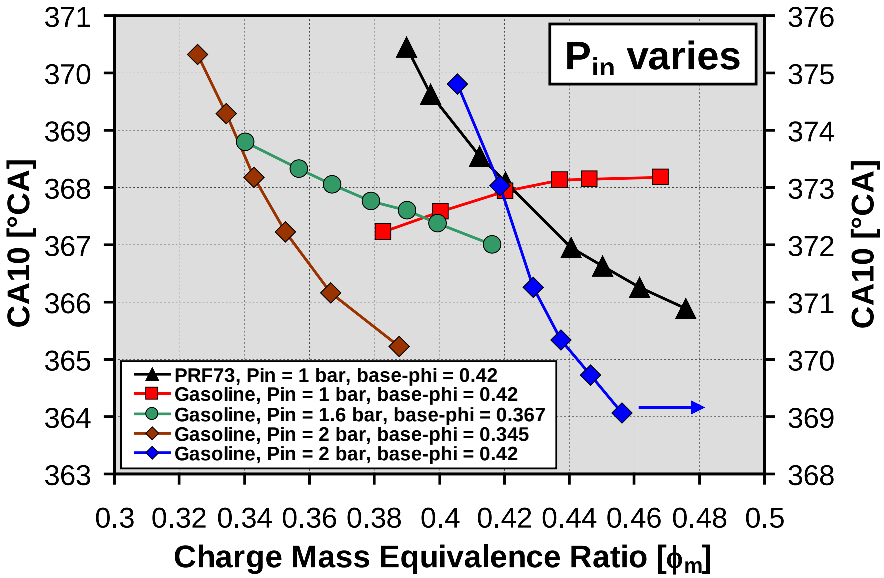




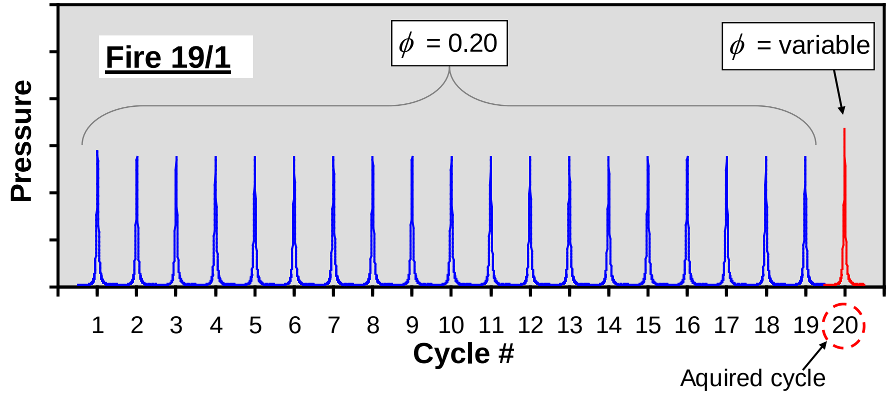
- Why does early-DI give better performance?
  – PLIF images show incomplete mixing ⇒ mixture stratification.

Φ-Sensitivity of Gasoline

- For mixture stratification to reduce HRR, fuel autoignition must be sensitive to variations in the local ϕ.
  - Prev. thought to require a 2-stage ignition fuel (*e.g.* PRF73).



- Use Fire19/1 technique to isolate fuel-chemistry effects from thermal effects.
  - Dec & Sjöberg *SAE 2004-01-0557*.
- Sweep ϕ above & below base fueling.
- P_{in} = 1 bar ⇒ chemistry not ϕ-sensitive; like iso-octane, γ effect dominates.
- P_{in} = 2 bar ⇒ strong ϕ-sensitivity more than PRF73.
- P_{in} = 1.6 bar ⇒ intermed. ϕ-sensitivity.

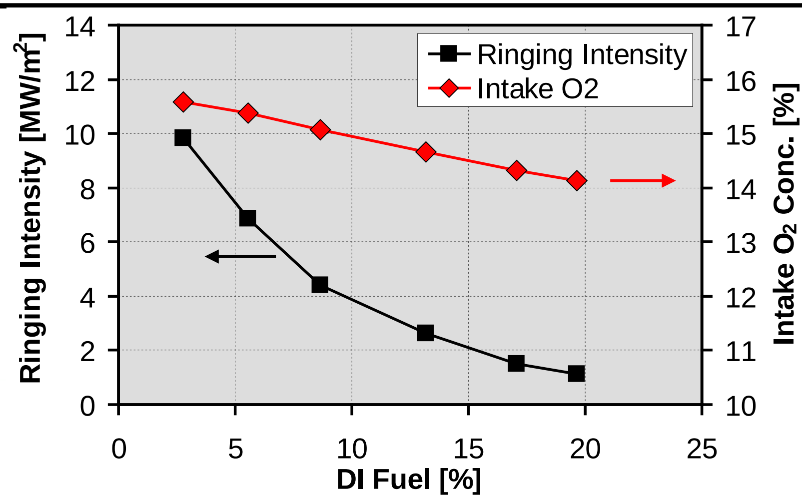


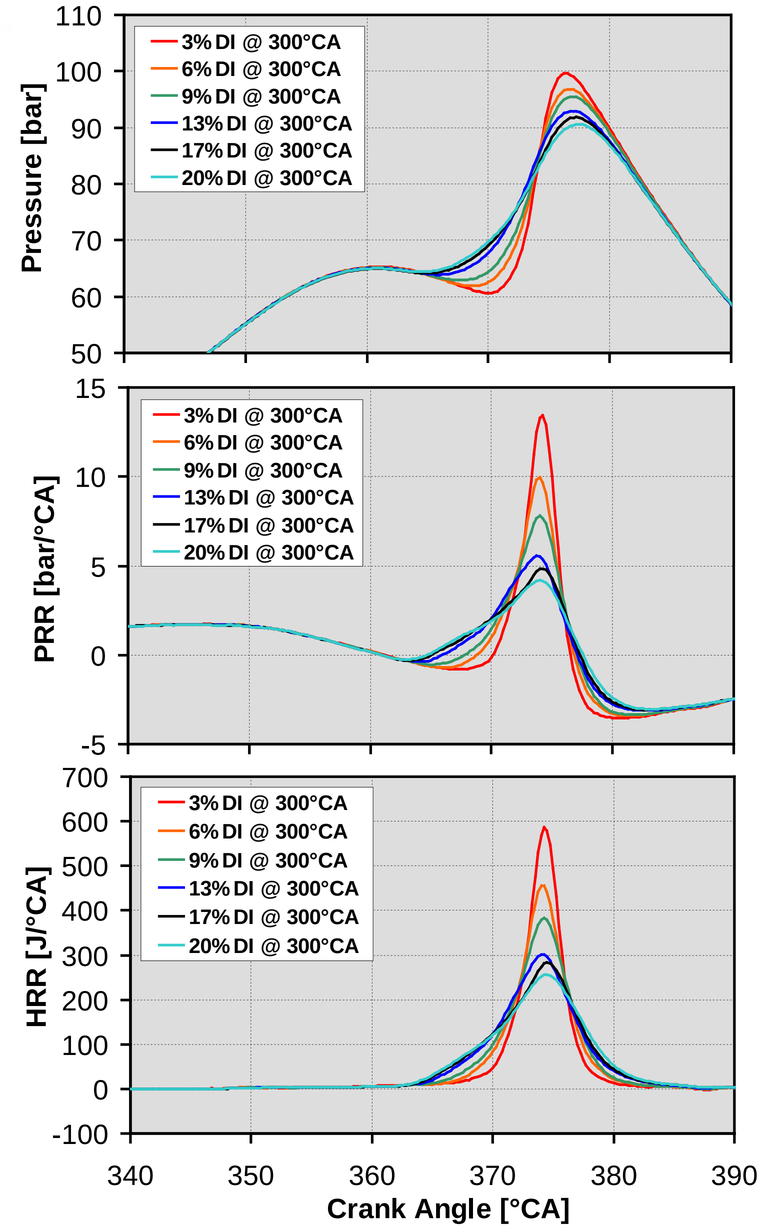
- With boost, gasoline autoignition strongly ϕ-sensitive. Not for P_{in} = 1 bar.

P_{in} = 2 bar: Controlled Mixture Stratification

- **Partial fuel stratification (PFS)** ⇒ premix most fuel & late DI up to 20%.
  - Vary DI timing or DI% to vary stratification.
- Large drop in ringing with increased DI%.
- Increased DI% ⇒ more regions of higher ϕ_m ⇒ autoignite faster ⇒ advances hot ignition for same CA50 ⇒ increases burn duration.
  - Reduces peak HRR, PRR_{max}, and P_{max}.
- Ultra-low NOx & soot. COV of $IMEP_g$ < 1.5%.

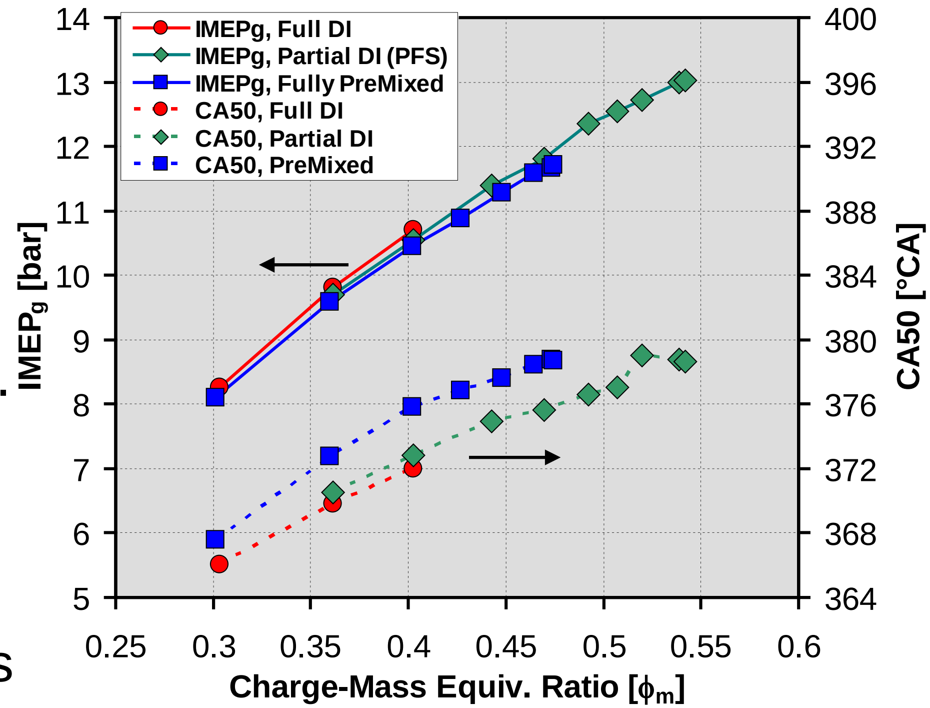
Hold: ϕ_m = 0.44, T_{in} = 60 C, CA50 = 374 CA





Extend High-Load Limit with PFS, P_{in} = 2 bar

- Reduced ringing with PFS allows higher fueling and/or advanced CA50.
- Premixed fueling ⇒ increase load from ϕ_m = 0.3 to knock/stability limit.
  - Retard CA50 so Ringing ≤ 5 MW/m² ⇒ Limit: $IMEP_g$ = 11.7 bar at ϕ_m = 0.47.
- Full early-DI fueling:
  - Some mixture stratification
  - Allows advanced CA50, but stability limit is $IMEP_g$ = 10.7 bar, ϕ_m = 0.40.
- PFS (partial DI) ⇒ much better stability ⇒ allows signif. higher loads.
  - Limit: $IMEP_g$ = 13.0 bar, ϕ_m = 0.54.
  - Approaching oxygen availability limit ⇒ 0.9% O_2 in exhaust.



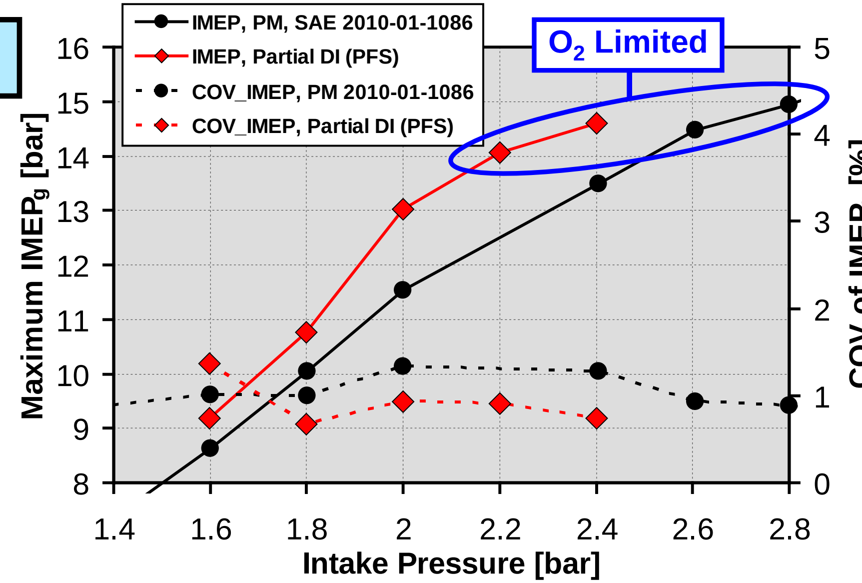
- Large reduction of HRR (PRR) allows
  - CA50 more advanced than premixed.
  - Higher thermal eff. and ringing reduced to 2 – 3 MW/m² ⇒ greater stability.

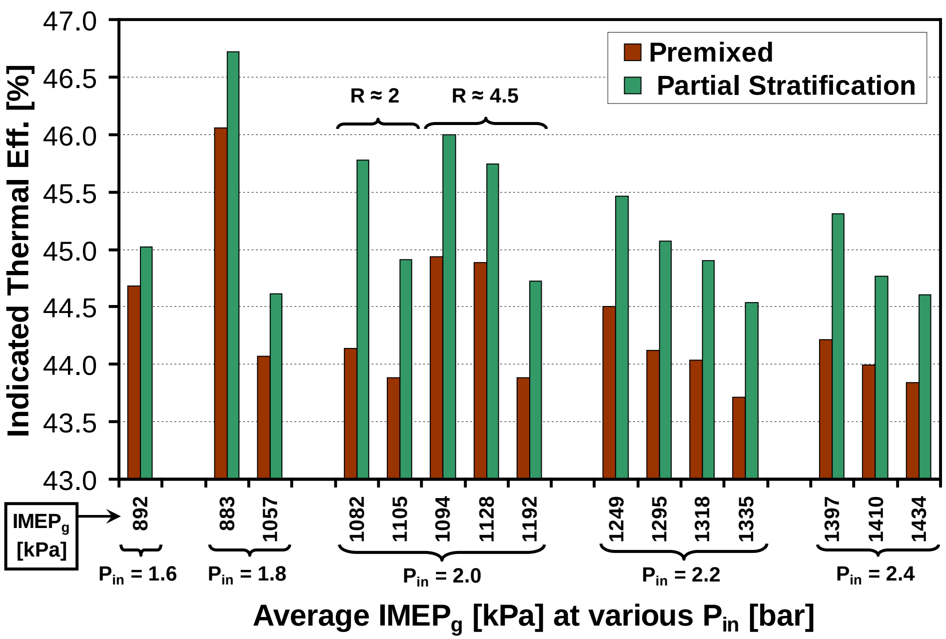
- PFS allows a large increase in load for gasoline boosted to P_{in} = 2 bar.

Load-Limit & Eff. Improvements at Various P_{in}

- Our initial investigation of boosted HCCI in SAE 2010-01-1086 showed
  $\Rightarrow$ maximum load attainable for well premixed HCCI at various boost levels.

- **PFS allows higher loads for all P_{in} tested.**
  - PFS quite stable $P_{in} \geq 2.0$ bar
    $\Rightarrow$ largest gain.
  - O_2 limited for $P_{in} \geq 2.2$ bar.
  - PFS less stable for P_{in} = 1.6 & 1.8 bar.
    > Lower ϕ-sensitivity.



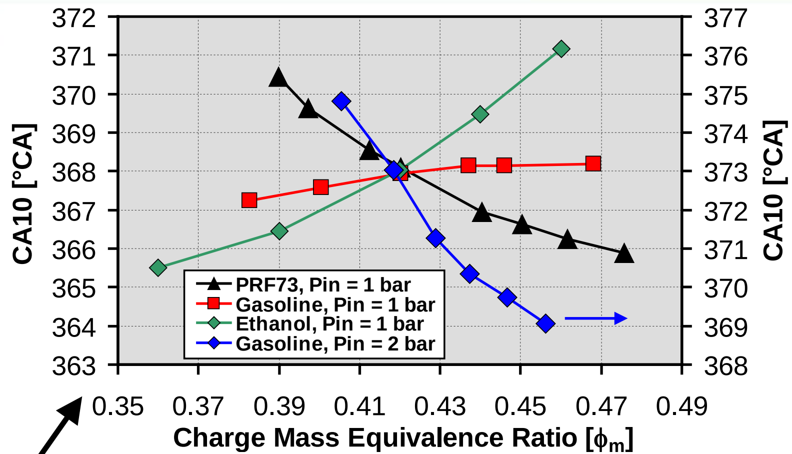


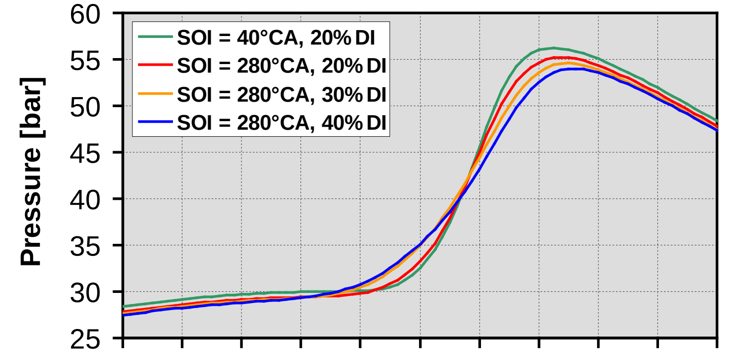
- Alternatively, PFS can allow CA50 advance for same ringing (PRR).
- T-E increases from 0.3 to 1.6% $\Rightarrow$ fuel economy gain of 0.7 – 3.6%.
- **PFS gives typical fuel economy improvement of 2 – 2.5%.**

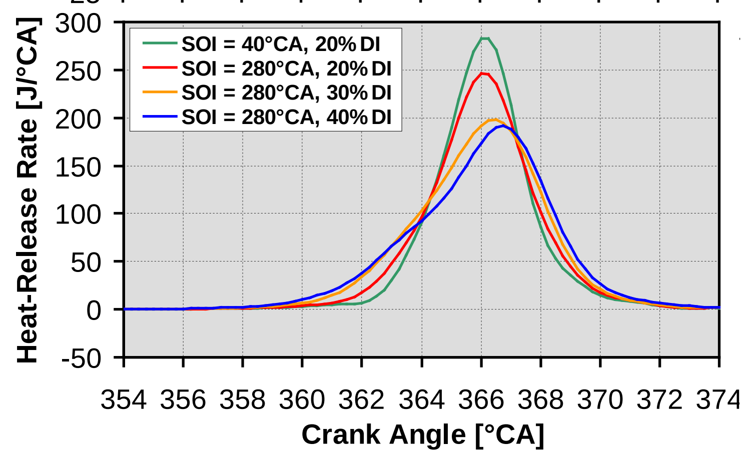
Ethanol-Fueled HCCI – Effects of PFS

- Ethanol is an important alternative fuel.
- Exhibits true single-stage ignition
  - Autoignition chemistry not ϕ-sensitive.
  - Very temperature sensitive.
- Also, a high heat of vaporization & much lower γ for a given ϕ than gasoline.
- Combination results in an inverse ϕ-sensitivity compared to boosted gasoline.
- Can we exploit this to reduce the HRR by using PFS to increase the TS?
- PRR and HRR are reduced with PFS due to increased TS.
  - Ignites lean-to-rich, opposite of boosted gasoline with PFS.
  - NOx just below US-2010 at conditions tested.

- PFS reduces HRR & PRR with ethanol, but benefit is much less than for boosted gasoline.







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: Support chemical-kinetic mechanism development, Pitz *et al*.
- SNL: 1) Collaborate on ethanol HCCI with SI alt.-fuels lab, Sjöberg *et al.*
  2) Collaborative project on LES modeling of HCCI, Oefelein *et al.*
- General Motors: Bi-monthly internet meetings ⇒ in-depth discussions.
  - Support GM modeling of boosted HCCI and TS with data and discussions.
- U. of Michigan: Support modeling TS, boundary-layer devel. & heat transfer.
- U. of New South Wales: Support modeling of ethanol-fueled HCCI.
- Chevron: **Funds-In project** on advanced petroleum-based fuels for HCCI.
- JBEI (Joint BioEnergy Institute): **Funds-In project** on 2nd generation biofuel, iso-pentanol, for HCCI.
- SNL-LDRD: **Funds-In project** on biofuels produced by fungi ⇒ collab. with researchers in basic chemistry (C. Taatjes *et al.*) & Biofuels (M. Hadi *et al.*).

Future Work

Thermal Stratification

- Complete current parametric study using side-view imaging to determine the of the effects of engine speed and intake temperature on TS.
- Extend parametric study to include: 1) independent variation of firedeck and piston-top temps, & 2) enhancing TS through increased turbulent convection.
  - Continue collaborations with J. Oefelein *et al.* on use of LES modeling of TS.

High-Efficiency, Boosted HCCI

- Expand studies of PFS for boosted gasoline-fueled HCCI: 1) effects of engine speed and load, & 2) improved mixture formation to improve stability.
  - Optical imaging of fuel distribution to assist improved mixture formation.
- Explore additional methods for increasing thermal efficiency of boosted HCCI $\Rightarrow$ Fuel effects, compression ratio, and Miller cycle.

Support of HCCI Modeling

- Continue collaborations with GM-research & U of Mich. on HCCI modeling.
- Continue to collaborate with LLNL on improving chemical-kinetic mechanisms of single components and gasoline-surrogate mixture.

Summary

- Improvements to side-view imaging provide T-maps showing both bulk-gas and boundary-layer thermal stratification (TS) simultaneously.
- No evidence of consistent flows transporting colder gas from near-wall regions into central bulk gas.
- Bulk-gas TS (which controls max. PRR) appears to result from in-cylinder turbulence producing turbulent structures extending from the wall.
  - Most cold pockets in bulk gas are structures attached to firedeck or piston top.
  - Bulk-gas TS reaches a maximum at TDC.
- Reducing T_{in} increases therm-eff. by reducing required EGR & heat transfer.
- Gasoline autoignition becomes strongly ϕ-sensitive with boost. $\Rightarrow$ Enables large reduction in HRR and PRR with partial fuel stratification (PFS).
- PFS significantly increases high-load limit of gasoline-fueled, boosted HCCI.
- PFS also effective for increasing thermal efficiencies of boosted HCCI.
  - NOx and soot emissions were ultra-low for all PFS conditions studied.
- Ethanol shows “inverse” ϕ-sensitivity due to strong thermal effects. $\Rightarrow$ Allows PFS to reduce HRR, but benefit is much less than for boosted gasoline.