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**

Overview

Timeline

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

Barriers

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

Budget

- Project funded by DOE/VT:
  FY11 – $750k
  FY12 – $760k

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 – thermal strat.
- Univ. of New South Wales, Australia
- Chevron – advanced fuels for HCCI
- 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 SCCI engines by industry.

<u>FY12 Objectives</u> ⇒ Increased Efficiency, High Loads, Improved Understanding

- <u>Improve the Efficiency of Boosted HCCI/SCCI</u>: Systematically investigate the effects of key engine operating parameters to determine:
  - Their effects on thermal efficiency.
  - The highest efficiency attainable with current engine configuration.
- <u>Effects of Gasoline Ethanol Content</u>: Determine the effects of expected variations in ethanol content of pump gasoline on HCCI/SCCI efficiency and high-load capability.
- <u>Investigate the changes in thermal stratification (TS)</u> with operating conditions ⇒ Speed, intake temperature (T_{in}), wall temperature and swirl.
- Support modeling of chemical-kinetics at LLNL and TS at 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/SCCI processes.

- Metal engine ⇒ conduct well-characterized experiments to isolate specific aspects of HCCI/SCCI combust. Determine cause-and-effect relationships.
  - Improved efficiency: Systematically vary operating parameters while holding other key parameters constant ⇒ T_{in}, fueling rate, speed, fueling strategy, P_{in}.
  - Ethanol content of gasoline: E0, E10, and E20 effects on performance.

- 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.

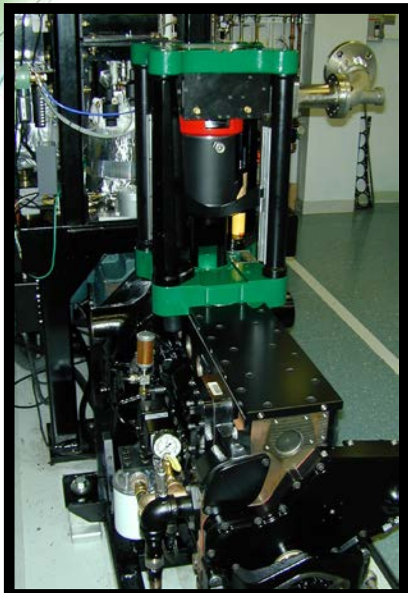
- Computational Modeling:
  - Support LLNL improvement of kinetic mechanisms ⇒ gasoline surrogate
  - Univ. of Michigan & GM ⇒ Modeling/analysis of thermal stratification (TS).

- Combination of techniques provides a more complete understanding.

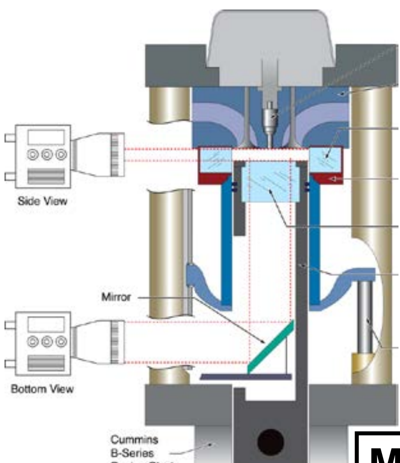
- Transfer results to industry: 1) physical understanding, 2) improved models, 3) data to GM to support analysis of TS and R&D of boosted HCCI engines.

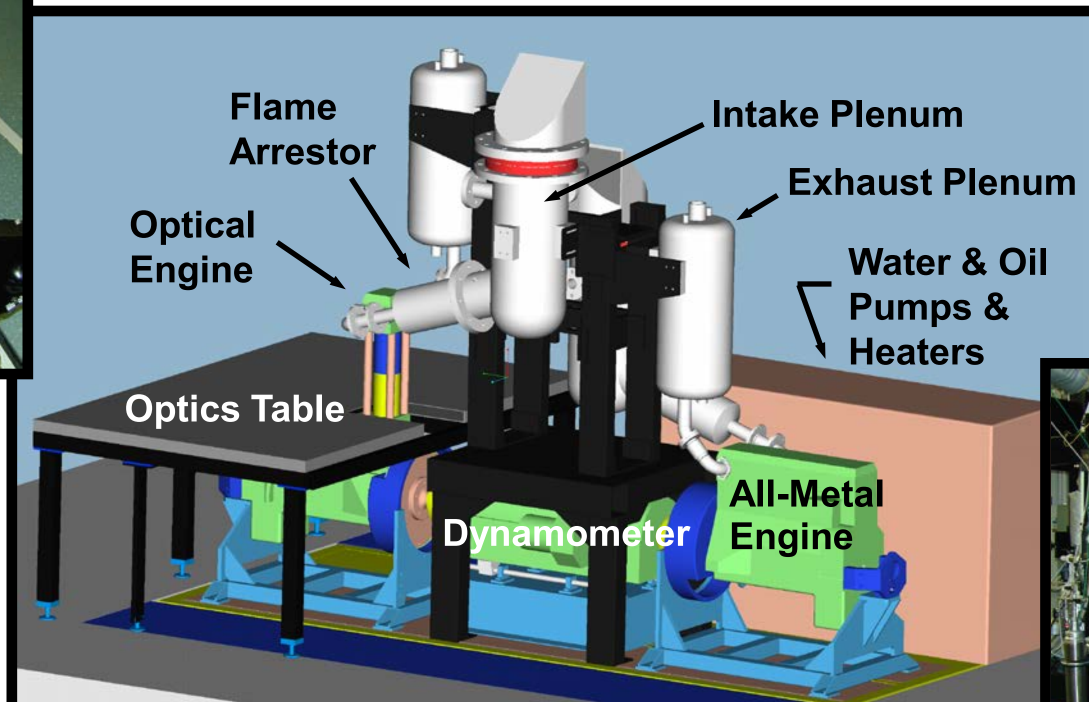
Sandia HCCI / SCCI Engine Laboratory

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

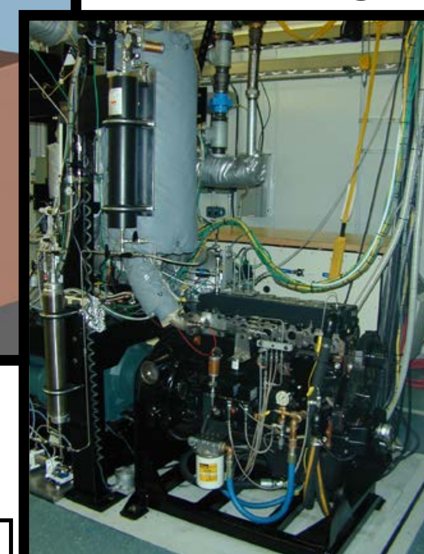


Optical Engine





All-Metal Engine



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

Metal-engine ⇒ Fuel is gasoline (AKI = 87), E10, E20

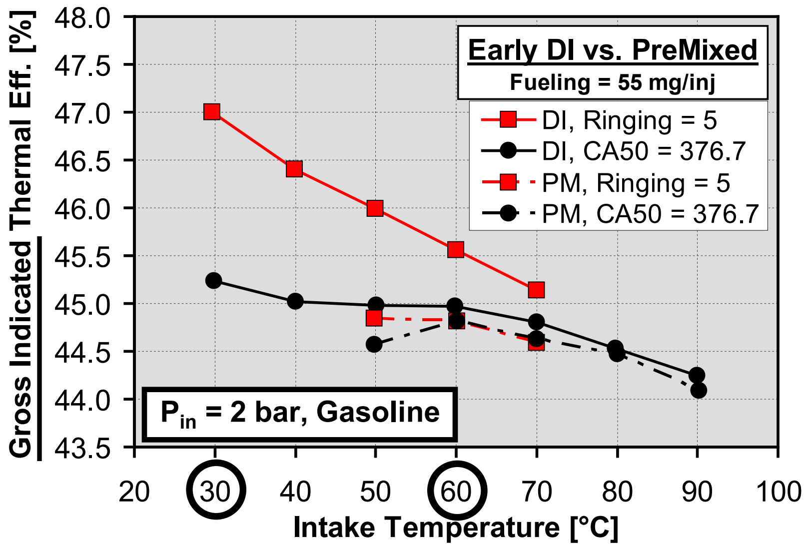
NO_x and soot emissions > 10x below US-2010

Accomplishments

- Determined effects of all main operating parameters on thermal efficiency. *(T_{in}, fueling rate, engine speed, fuel-type, fueling strategy, and P_{in})*
  - Found optimal values within constraints (i.e. acceptable ringing, emissions, etc.)
  - Combined optimal values to obtain highest eff. for current engine config. & fuels.
- Demonstrated indicated thermal efficiencies of 47 – 48% for loads from 8 to 16 bar $IMEP_g$ ⇒ for current CR = 14:1 configuration.
- Evaluated performance affects of increasing ethanol content of gasoline, from E0 ⇨ E10 ⇨ E20. (E10 complete, E20 initial results ⇒ on track for FY)
  - Showed max. load increase from 16.3 ⇨ 18.1 ⇨ 20.0 bar $IMEP_g$, respectively.
- Significantly improved temperature-map imaging ⇒ 1) resolution, 2) SNR (signal/noise), & 3) post-processing to remove laser-sheet schlieren effects.
- Quantified variations in TS over range of conditions ⇒ speed, T_{in}, T_{wall}, swirl
  - Conducted a PDF analysis of the TS at various conditions.
  - Initiated analysis of cold-pocket size.
- Supported chemical-kinetic model development at LLNL, and TS modeling at U. Michigan & General Motors ⇒ provided data and analysis.

Improving Thermal Efficiency

- Advanced engines using HCCI or partially stratified variations termed "SCCI" provide high efficiencies (~30% improvement over SI).
  - Use light-end distillates efficiently, and no aftertreatment for NO_X and PM.
- Although thermal efficiencies of HCCI/SCCI are already very good, further increases are desirable.
- Conduct a systematic study of factors affecting thermal efficiency (T-E) and seek the highest efficiency for our current engine configuration.
- Initial work presented last year showed T-E increased with reduced T_{in}.
  1. Const. CA50 ⇒ Moderate increase in T-E
     > Higher γ (↓EGR & ↓T) & less heat loss.
  2. Const. ringing = 5 MW/m^2 (const. PRR)
     ⇒ Premixed: T-E similar to const. CA50
     ⇒ Early-DI: large increase in T-E.
     > Fuel not completely mixed ⇒ partial fuel stratification (PFS) effect reduces HRR to allow CA50 advance (discussed later).

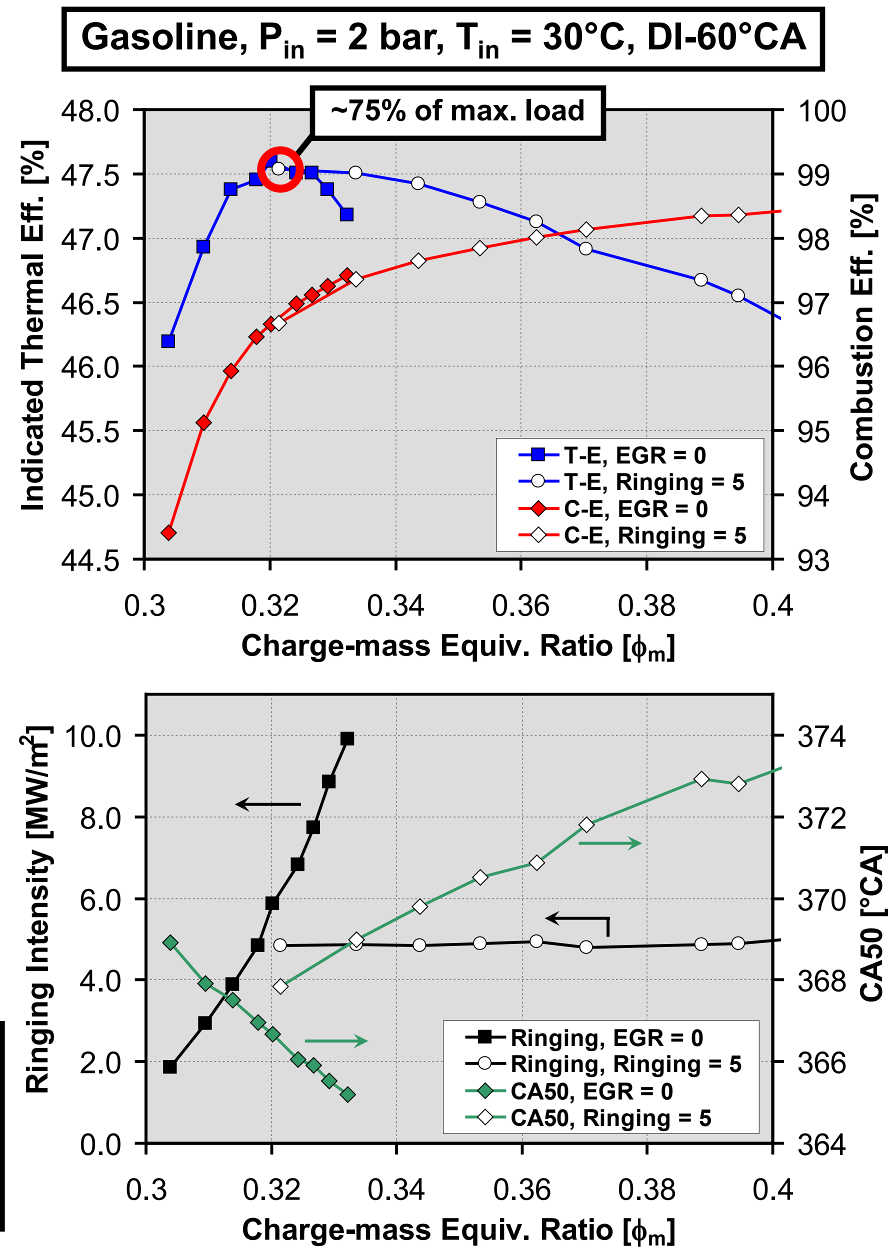


- **Conclusion: Use the lowest T_{in} possible.**

- Early-DI ⇒ use T_{in} = 30°C. Premixed ⇒ T_{in} = 60°C, no fuel condensation.

Fueling-Rate Effects

- Increase fueling from lowest ϕ_m for stable combustion with EGR = 0%.
  - T-E increases with improved C-E.
  - Ringing increases due to higher ϕ_m and more advanced CA50.
  - R > 5 or 6 ⇒ knock & incr. heat loss.
- Trade-off between improved C-E and heat loss ⇒ T-E drops for ϕ_m > 0.32.
  - **T-E peaks at 47.6%, $IMEP_g$ ~9.5 bar**
- <u>Hold Ringing = 5</u> using EGR to retard CA50 ⇒ much higher loads.
- Initial CA50 retard hardly affects T-E, but reduction in T-E increases for CA50 > ~370°CA. EGR also up.

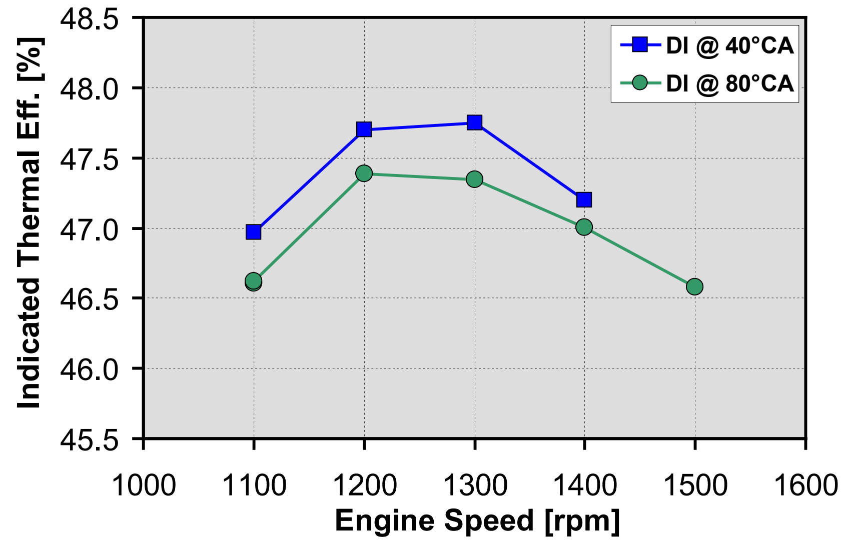


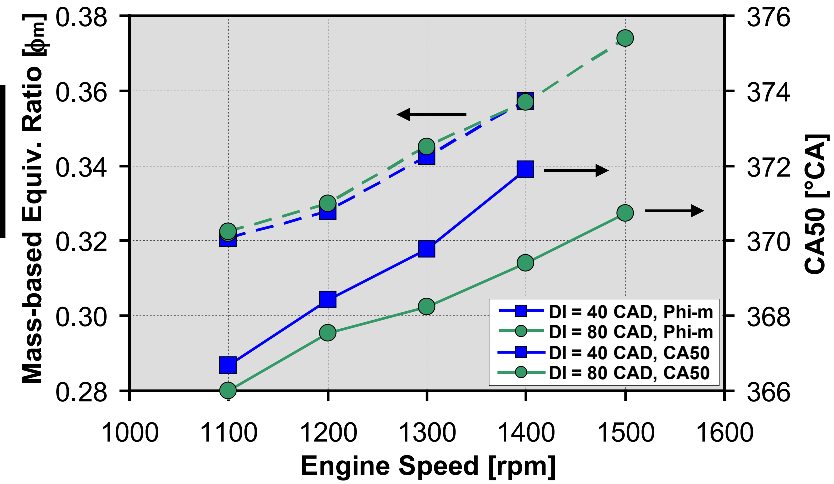
- <u>Best T-E</u> ⇒ Adv. CA50 up to R ≈ 5 for each load (ϕ_m). ⇒ Lower loads give higher T-E as long as C-E ≥ ~96.5%.

Engine Speed

- At each speed, find highest efficiency point, using procedure on previous slide.
  - Use Early-DI fueling with T_{in} = 30°C.
  - Increase fueling (ϕ_m) to improve C-E and advance CA50 up to Ringing ≈ 5.
    - Reached C-E ~96.5%, w/o EGR.
- **T-E peaks between 1200 & 1300 rpm.**
- Higher fueling required at higher speeds.
  - With higher fueling, CA50 must be more retarded to keep Ringing ≤ 5.
- **Trade-off between reduced heat losses & more CA50 retard as speed increases.**
- T-E similarly high for 1200 or 1300 rpm.
- **Use 1200 rpm to be consistent with previous data.**

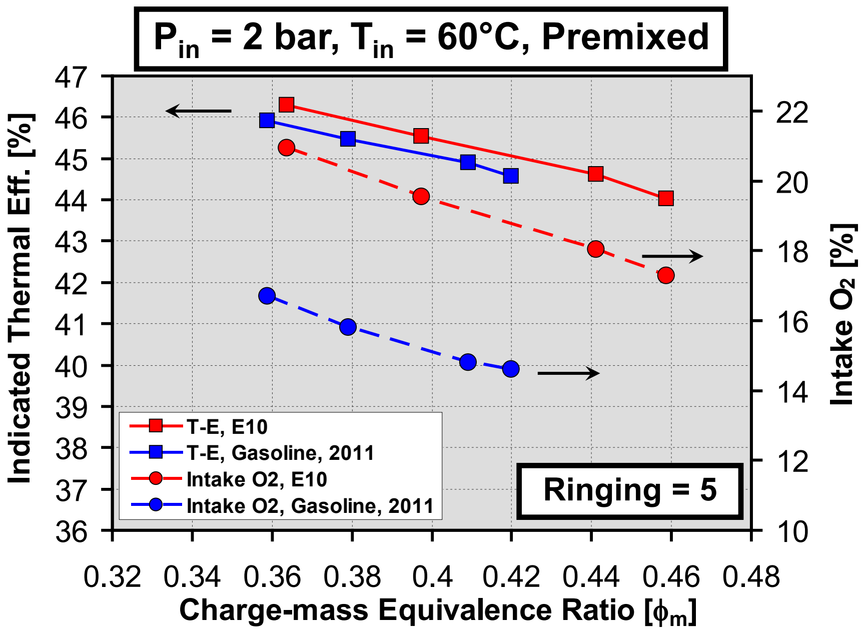
Gasoline, P_{in} = 2 bar, T_{in} = 30°C, Early-DI





Fuel Type: E10 vs. Gasoline

- A large fraction of the gasoline sold in the US contains up to 10% ethanol.
- Our E10 is blended from our ON = 87 gasoline + neat ethanol.
  - Assuming a ON of 99.5 for ethanol, our E10 has an **AKI = 88.1**
  - Between regular & mid-grade pump gasoline.
- For P_{in} = 2 bar, E10 is less reactive.
  - Significantly less EGR required to keep Ringing ≤ 5 (CA50s similar).
  - Higher γ increases efficiency.
- T-E is ~0.4 T-E-percentage units higher with E10 (an increase of 0.9%)



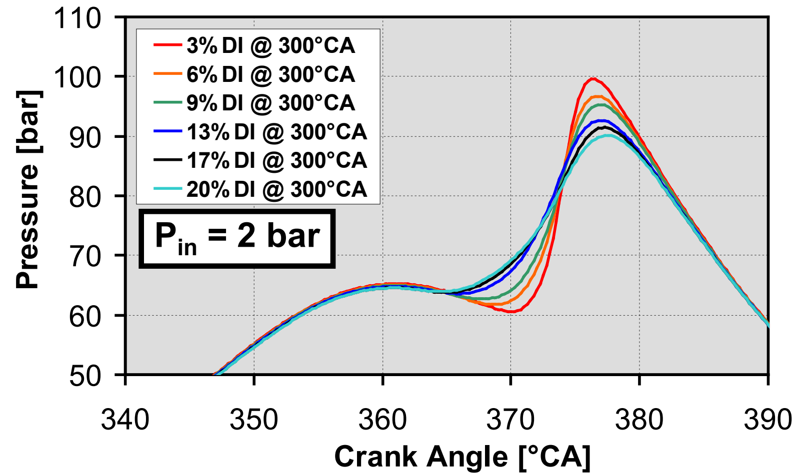
- E10 offers a modest T-E advantage for boosted operation.

Fueling Strategy: PM, PFS, Early-DI

<u>Previous work, SAE 2011-01-0897</u>

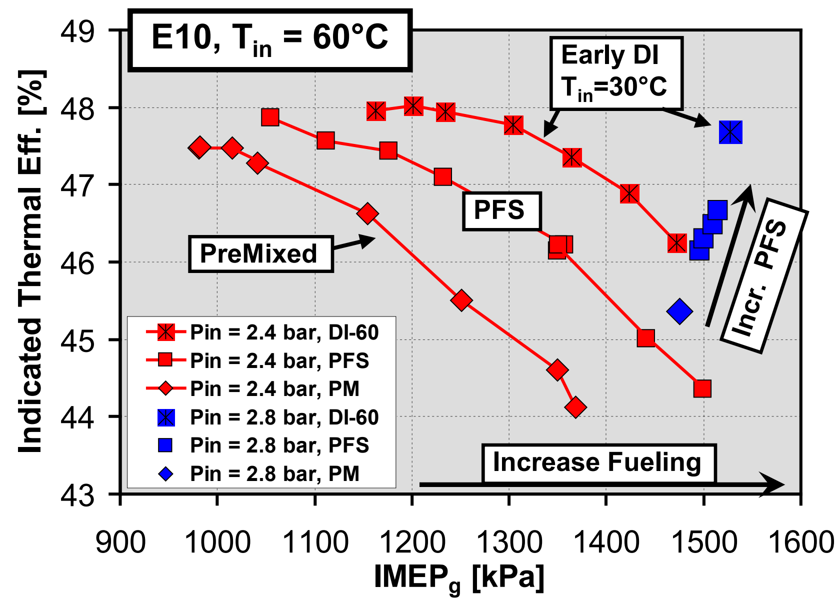
- Gasoline autoignition becomes sensitive to local ϕ with intake boost.
- Allows use of partial fuel stratification (PFS) to significantly reduce PRR_{max}.
  - Premix ≥ 80% of fuel, late-DI for rest.
  - Higher loads for same CA50.
  - Advance CA50 for higher efficiency.

Gasoline, ϕ_m = 0.44, T_{in} = 60°C, CA50 = 374°CA



<u>Recent Results with E10 (C-E ≥ 96%)</u>

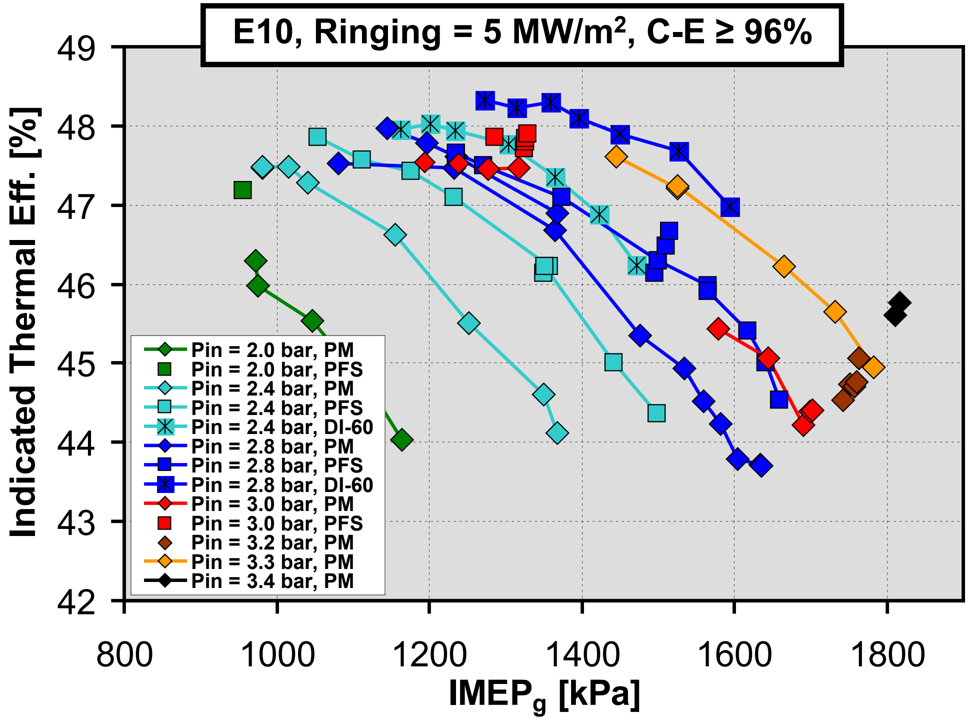
- PFS is also effective with E10 (~9%DI).
  - Higher T-E and higher load.
- Early-DI fueling, further increases T-E.
  - Mixture similar to PFS, and T_{in} reduced to 30°C, less heat loss & higher γ.
- Example at P_{in} = 2.8 bar, const. fueling shows increased T-E with increasing PFS and early-DI with T_{in} = 30°C .



- PFS and Early-DI fueling increase T-E significantly for the same load.

Intake Pressure and Fueling Strategy

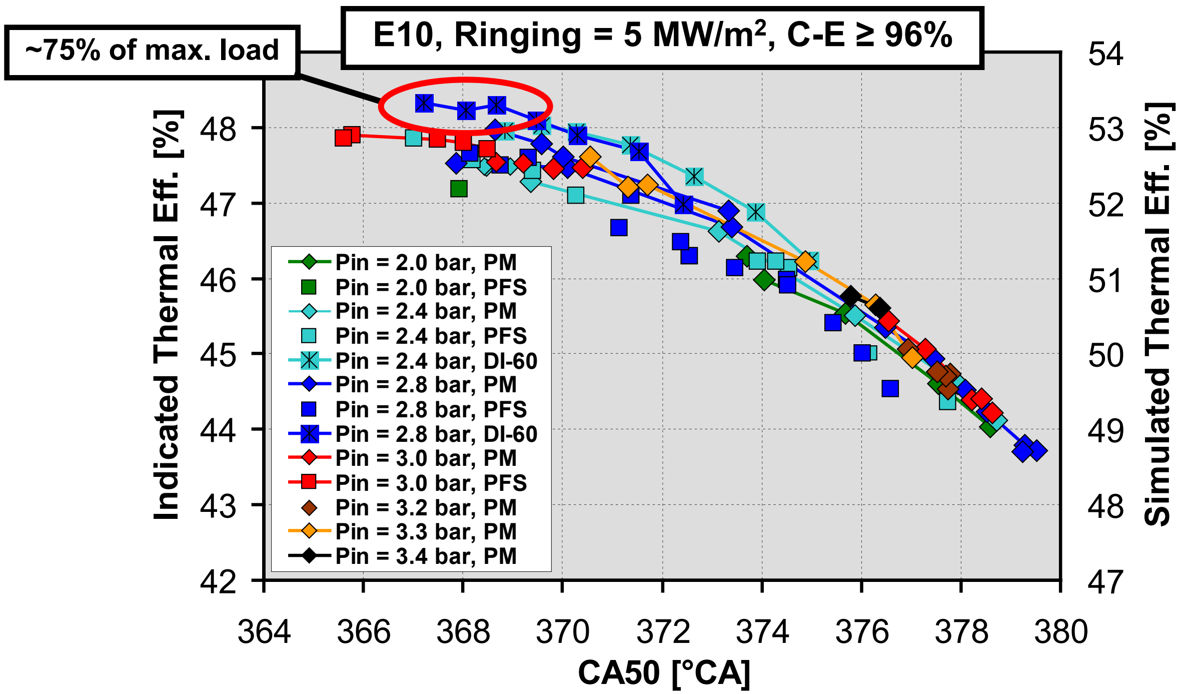
- Data acquired for wide range of intake pressures (P_{in} = 2.0 to 3.4 bar), and three fueling strategies (PM, PFS, and Early-DI) show similar trends.
  - Load increases with boost, but curve shape is similar.



- For each P_{in}, T-E decreases with increased load mainly due to requirement to retard CA50 to prevent excessive ringing. EGR also increases with load.
- Replot T-E data against CA50.

Combustion Phasing (CA50)

- All Premixed and PFS data for T_{in} = 60°C collapse into a single band when plotted against CA50.
  - Appears to be reaching a max. at ~365°CA ⇒ reasonable with Heat-Transfer.



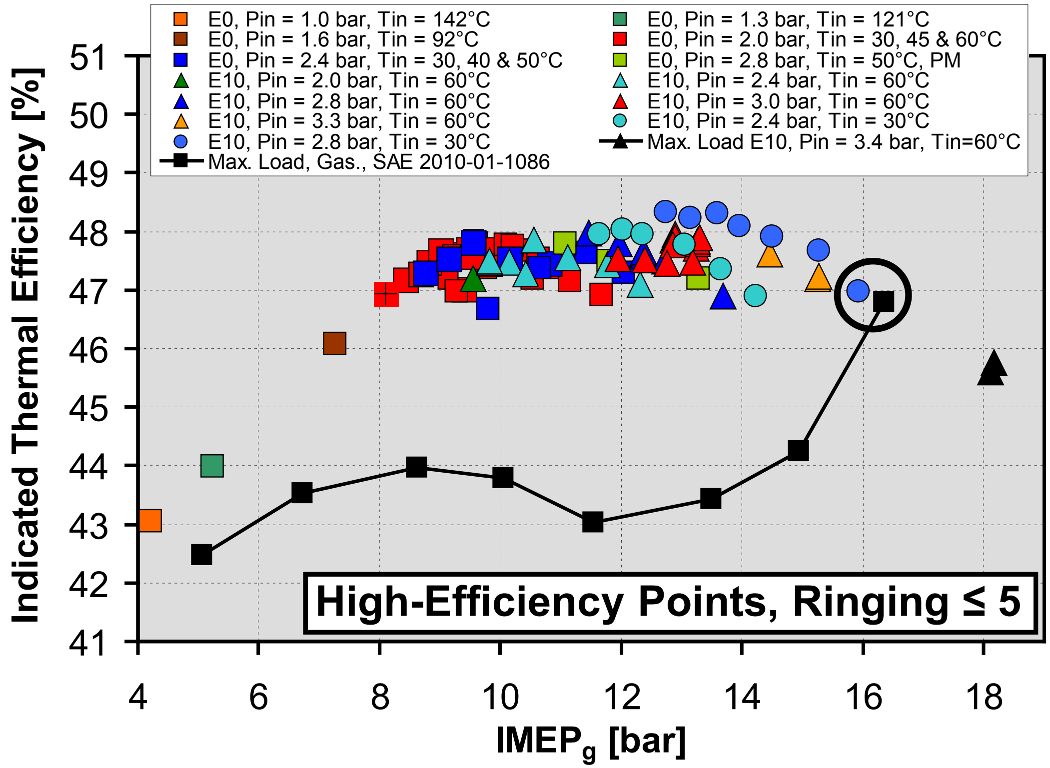
Simulation

– Constant fueling
– Constant EGR
– Woschni H-T for max. T-E @ 365°CA

- Compare with idealized curve ⇒ agrees well. EGR effect in real data.
- Little advantage to advancing CA50 beyond ~368 – 370°CA.
- With Early-DI fueling & T_{in} = 30 C, T-E increases additional 0.5 - 1 TE-units.
- Max. T-E for this engine config. 48.3% with P_{in} = 2.8 bar (P_{back} = 2.82 bar).

Summary of Efficiency Improvements

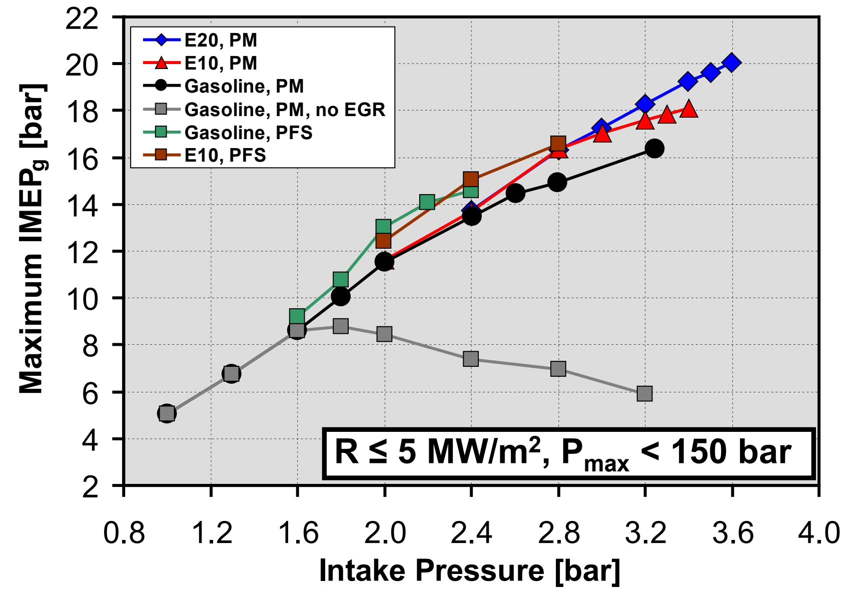
- T-E increased well above the values for the high-load limit from initial boost study in SAE 2010-01-1086.

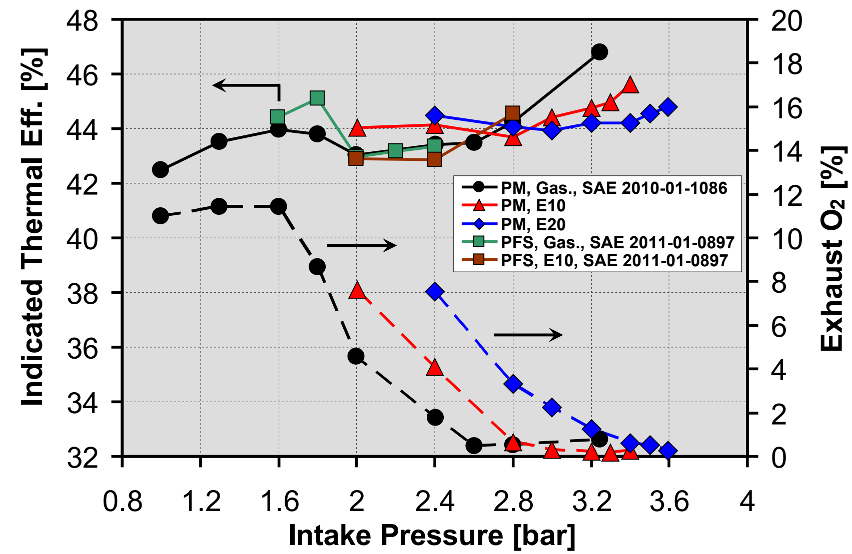


- Gasoline ⇒ reached T-Es of 47 - 47.8% from 8 to 13.5 bar $IMEP_g$.
- E10 ⇒ reached T-Es of 47 – 48.3% from 9.5 to 16 bar $IMEP_g$
  - Achieve 16 bar $IMEP_g$, 47% T-E with P_{in} = 2.8 bar, vs. 3.25 bar for gasoline.

High-Load Limit: Gasoline ⇨ E10 ⇨ E20

- Gasoline reactivity increases with boost ⇒ use EGR to control CA50.
  - Blending with ethanol significantly reduces EGR requirement with boost.
  - More air in charge ⇒ higher fueling.
- **E0:** O_2 limited for $P_{in} \geq 2.6$ bar ⇒ Load limit = 16.3 bar $IMEP_g$.
- **E10:** ⇒ O_2 limited for $P_{in} \geq 2.8$ bar ⇒ Load limit = 18.1 bar $IMEP_g$.
- **E20:** ⇒ O_2 limited for $P_{in} \geq 3.6$ bar ⇒ **Load limit = 20.0 bar $IMEP_g$.**
- Ringing ≤ 5, ultra-low NO_X & soot.
- T-E ⇒ Higher for E10 & E20 at P_{in}= 2 & 2.4 bar, less EGR. ⇒ Lower at P_{in} >2.8 bar, more CA50 retard w/ increased load.
- PFS can increase load up to ~15%, for $P_{in} \geq$ ~2 bar, if O_2 is sufficient.



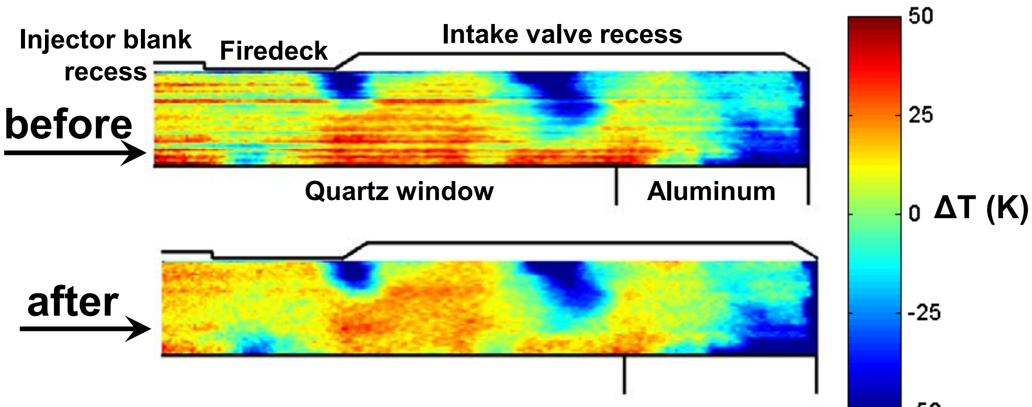


- High-loads limited by P_{max} < 150 bar.

Improved Thermal-Stratification Imaging

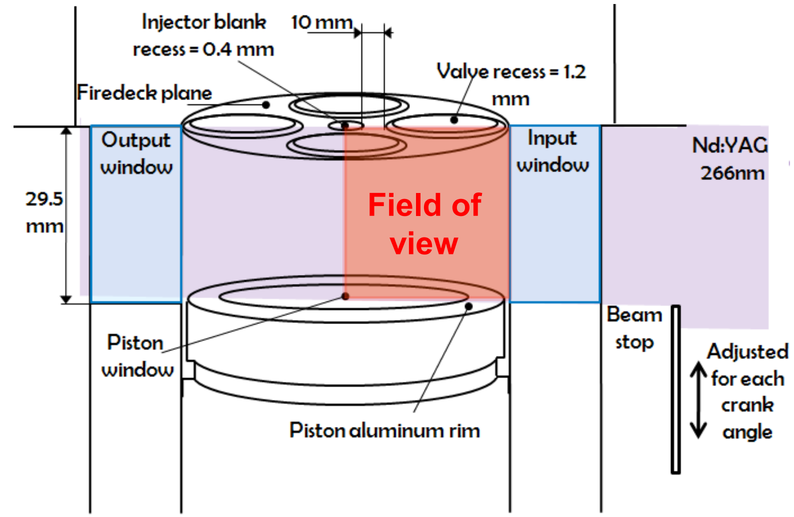
- Temperature-maps (T-maps) derived from PLIF images with toluene tracer.
- Switch to non-intensified, back-illum. CCD camera, mounted closer.
  ⇒ Greatly improves resolution & S/N.
- Allows accurate image analysis.
- Improved image correction techniques remove stripes with less effect on T.
  ⇒ Accurate Std-Dev of T-maps.

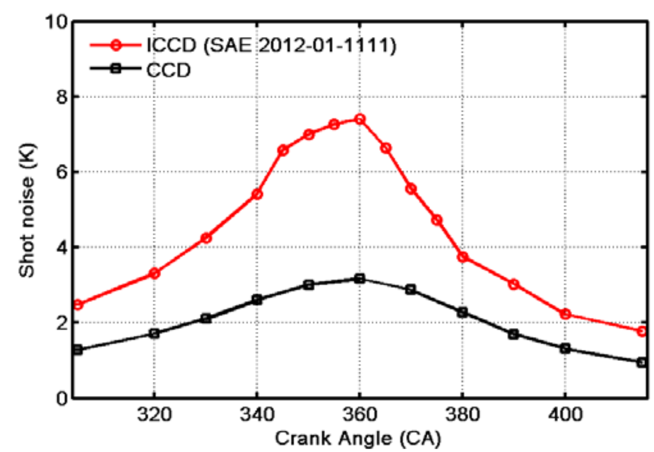
- **TS results mainly from cold structures.**



New shot-to-shot beam steering correction.

Side-view imaging shows bulk-gas & wall regions





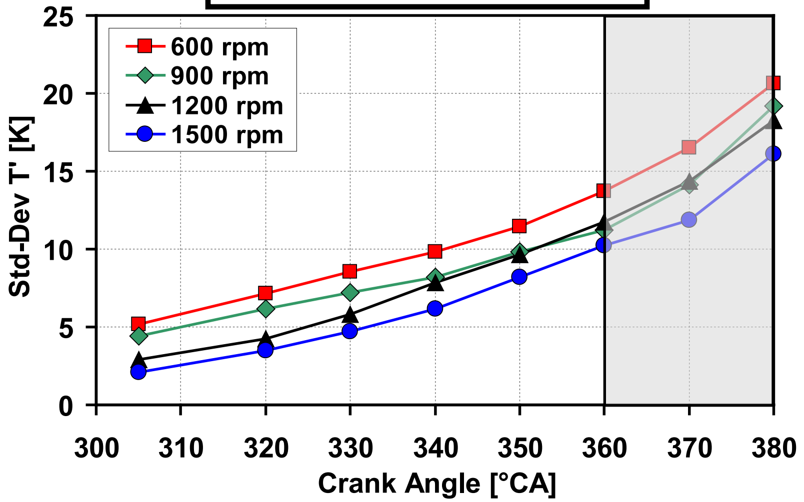
CCD vs ICCD doubles resolution and reduces shot noise at TDC by 2.4x

Effect of Engine Speed on TS

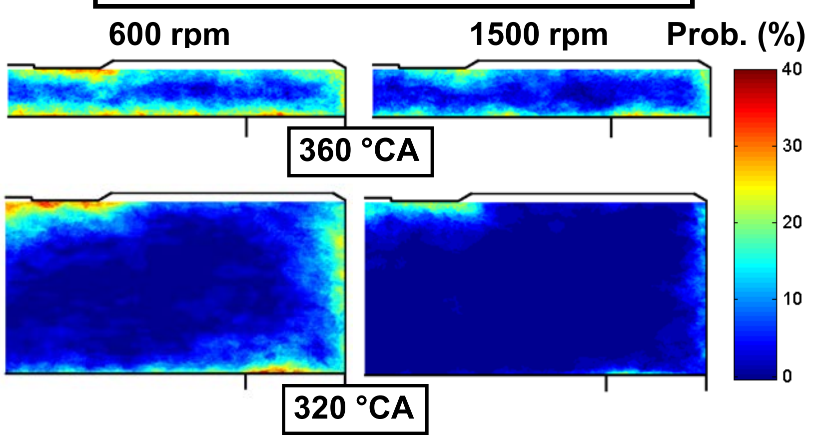
- Quantify TS as the Std-Dev of T'-maps
  ⇒ avg. Std-Dev of 100 cycles.
- TS increases through compression stroke.
- More TS at lower speeds.
- In agreement, image analysis shows greater probability of cold structures at lower speeds.
- Competing effects of:
  1. More time for heat transfer @ lower speeds
  2. Higher gas velocities @ higher speeds.
- Increased time appears to dominate over the potential for higher turbulence with increased gas velocities.

- **TS increases with decreased speed.**

Speed Effects on TS

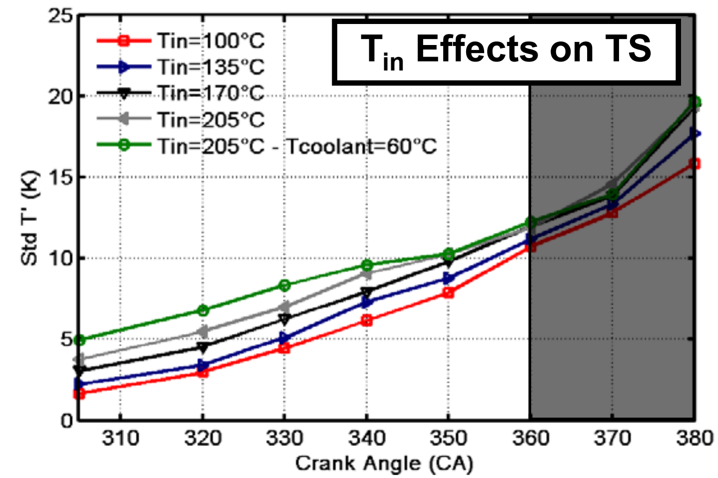


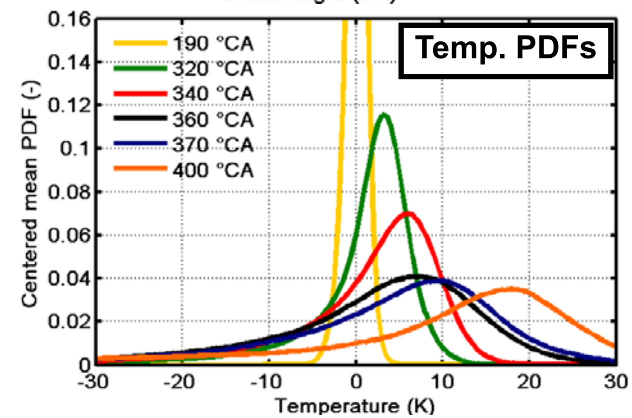
Probability of Cold Structures

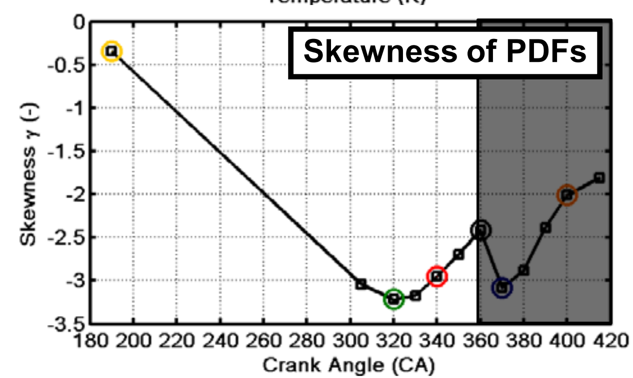


Effects of T_{in} and $T_{coolant}$ on TS

- TS increases with increasing T_{in}
  $\Rightarrow$ also with decreased $T_{coolant}$
- Expected that increased
  $\Delta T = T_{bulk\text{-}gas} - T_{wall}$ would increase TS.
- However, TS converges for CA ≥ 340°
  - Mainly because TS curves for the higher T_{in} (and greater ΔT) begin to flatten.
- Possibly due to over mixing reducing the TS.
  $\Rightarrow$ Effect should be larger for larger ΔT.
- PDFs of temperature distribution also indicate that over mixing could be occurring.
  - Negative skewness indicates that the PDF width is increased by mixing in cold gases.
  - Less skewness for CA > 330° suggests mixing out bulk-gas faster than bringing in new cold gas.







- **TS increases with increased T_{in} & lower $T_{coolant}$, but gain appears less than expected by TDC.**

Collaborations

- Project is conducted in close cooperation with U.S. Industry through the Advanced Engine Combustion (AEC) / HCCI Working Group, under a memorandum of understanding (MOU).
  - Ten OEMs, Five energy companies, Four national labs, & Several universities.
- LLNL: Support development of chemical-kinetic mechanism for gasoline surrogate mixture, Pitz *et al*.
- General Motors: Frequent internet meetings ⇒ in-depth discussions.
  - Provide data to support GM efforts on boosted HCCI & in modeling TS (with UM).
- U. of Michigan: Collaborate on modeling and analysis of TS and boundary-layer development ⇒ provide data and in-depth discussions (with GM).
- U. of New South Wales: Support modeling of ethanol-fueled HCCI.
- Chevron: **Funds-In project** on advanced petroleum-based fuels 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

Increased Efficiency and Performance of Boosted HCCI

- Explore increasing the thermal efficiency of boosted HCCI by raising the compression ratio (or expansion-ratio only using a Miller-cycle cam).
- Determine the performance potential of various realistic fuels:
  - Complete investigation of effects of ethanol content of gasoline (E0 ⇨ E20).
  - Expand study to include premium gasoline ⇒ potential compared to E10 or E20.
- Work w/ Cummins to modify cyl. head for spark plug for studies of SA-HCCI.

Thermal Stratification

- Expand current studies to: **1)** further investigate whether over-mixing limits TS at some conditions, **2)** include variation of piston-top T, & **3)** flow effects.
  - Potential collaboration with J. Oefelein *et al.* for LES modeling of TS.
- Investigate the potential of obtaining Boundary-Layer Profiles at the piston-top surface from T-map images ⇒ simultaneous T_{wall} & heat-flux data.

Support of HCCI Modeling

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

Summary

- Results presented have significantly improved fundamental understanding of HCCI / SCCI with respect to the barriers of: 1) increased efficiency, 2) increased load, and 3) improved understanding of in-cylinder processes.

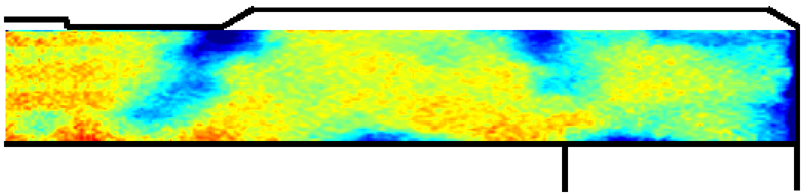
- Examined all key operating parameters affecting thermal efficiency (T-E) of boosted HCCI / SCCI engines ⇒ determined tradeoffs and limits.
  - Achieved highest gross-ind. T-E for current engine config. and fuel-set of 48.3%.
  - Demonstrated T-Es of 47-48% from 8 – 16 bar $IMEP_g$ using E0 & E10 gasolines.
- Showed that Partial Fuel Stratification significantly improves T-E across the fuel-load range for various P_{in} ⇒ and it increased high-load limit for given P_{in}.
- Early-DI fueling gives a PFS-like mixture with similar benefits, and it allows a lower T_{in} = 30°C without fuel condensation for a further increase in T-E.
- For boosted HCCI/SCCI, E10 gives higher T-E and higher loads than E0.
- Extended the high-load limit by increasing ethanol content E0 ⇨ E10 ⇨ E20. ⇒ Achieved high-loads of 18.1 & **20.0 bar $IMEP_g$** for E10 & E20, respect'ly.
- Showed TS increases with engine speed, T_{in}, lower $T_{coolant}$, and swirl.
  - Discovered that over mixing may be reducing the TS during late compression for higher T_{in} and lower $T_{coolant}$ conditions.

Technical Backup Slides

Definitions of T-maps

T-map ($T=\bar{T}+T'$)

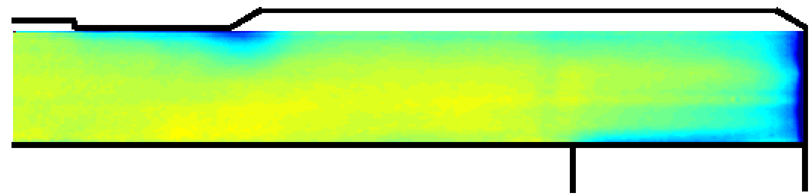
Total thermal stratification

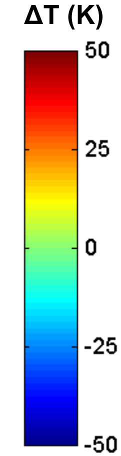


- Includes both the consistent boundary layers at the walls and the fluctuating TS in the bulk gas.

$\bar{T}$-map

Average thermal stratification

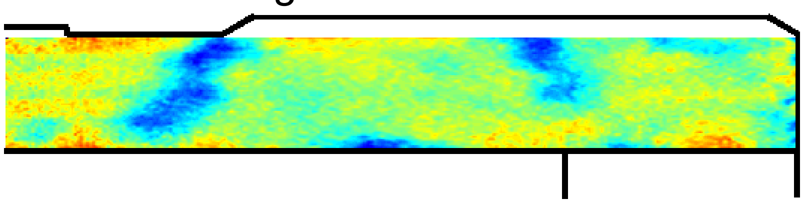




- Average of the 100 T-maps.
- Shows only the consistent TS patterns.

T'-map

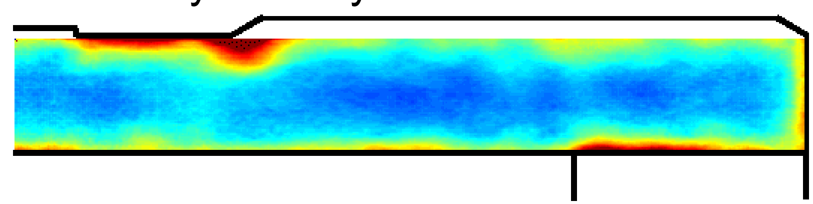
Fluctuating thermal stratification

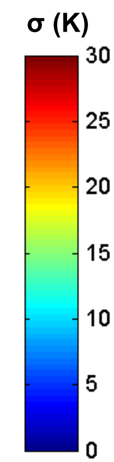


- Driven by in-cylinder turbulence.
- Most important for controlling PRR by sequential auto-ignition in HCCI engines.

T_{RMS}

Cycle-to-cycle variation





- RMS of the 100 T-maps.
- Shows the location of the cycle-to-cycle temperature variations.