HCCI and Stratified-Charge CI Engine
Combustion Research

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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
● 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**

**Project objective:** to provide the fundamental understanding (science-base) required to overcome the technical barriers to the development of practical HCCI or SCCI engines by industry.

**FY12 Objectives ⇒ Increased Efficiency, High Loads, Improved Understanding**

- **Improve the Efficiency of Boosted HCCI/SCCI:** Systematically investigate the effects of key engine operating parameters to determine:
  - Their effects on thermal efficiency.
  - The highest efficiency attainable with current engine configuration.

- **Effects of Gasoline Ethanol Content:** Determine the effects of expected variations in ethanol content of pump gasoline on HCCI/SCCI efficiency and high-load capability.

- **Investigate the changes in thermal stratification (TS) 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 $\Rightarrow$ 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 $\Rightarrow T_{in}$, fueling rate, speed, fueling strategy, $P_{in}$.
  - **Ethanol content of gasoline**: E0, E10, and E20 effects on performance.

- Optical engine $\Rightarrow$ 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 $\Rightarrow$ gasoline surrogate
  - Univ. of Michigan & GM $\Rightarrow$ 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.
Matching all-metal & optical HCCI research engines.
- Single-cylinder conversion from Cummins B-series diesel.

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

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

$\text{NO}_x$ and soot emissions > 10x below US-2010
Accomplishments

- Determined effects of all main operating parameters on thermal efficiency. $(T_{in}, \text{fueling rate}, \text{engine speed}, \text{fuel-type}, \text{fueling strategy}, \text{and} \ P_{in})$
  - 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 $\Rightarrow$ E10 $\Rightarrow$ E20. (E10 complete, E20 initial results $\Rightarrow$ on track for FY)
  - Showed max. load increase from 16.3 $\Rightarrow$ 18.1 $\Rightarrow$ 20.0 bar IMEP$_g$, respectively.

- Significantly improved temperature-map imaging $\Rightarrow$ 1) resolution, 2) SNR (signal/noise), & 3) post-processing to remove laser-sheet schlieren effects.

- Quantified variations in TS over range of conditions $\Rightarrow$ 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 $\Rightarrow$ 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\textsubscript{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\textsubscript{in}.
  1. Const. CA50 \Rightarrow Moderate increase in T-E
     - Higher \( \gamma \) (\( \downarrow \)EGR & \( \downarrow \)T) & less heat loss.
  2. Const. ringing = 5 MW/m\textsuperscript{2} (const. PRR)
     \Rightarrow Premixed: T-E similar to const. CA50
     \Rightarrow Early-DI: large increase in T-E.
     - Fuel not completely mixed \Rightarrow partial fuel stratification (PFS) effect reduces HRR to allow CA50 advance (discussed later).

- Conclusion: Use the lowest T\textsubscript{in} possible.
- Early-DI \Rightarrow use T\textsubscript{in} = 30°C. Premixed \Rightarrow T\textsubscript{in} = 60°C, no fuel condensation.
**Fueling-Rate Effects**

- Increase fueling from lowest $\phi_m$ for stable combustion with EGR = 0%.
  - T-E increases with improved C-E.
  - Ringing increases due to higher $\phi_m$ and more advanced CA50.
  - R > 5 or 6 $\Rightarrow$ knock & incr. heat loss.

- Trade-off between improved C-E and heat loss $\Rightarrow$ T-E drops for $\phi_m > 0.32$.
  - T-E peaks at 47.6%, IMEP$_g$ ~9.5 bar

- Hold Ringing = 5 using EGR to retard CA50 $\Rightarrow$ much higher loads.

- Initial CA50 retard hardly affects T-E, but reduction in T-E increases for CA50 $> \sim 370^\circ$CA. EGR also up.

- Best T-E $\Rightarrow$ Adv. CA50 up to $R \approx 5$ for each load ($\phi_m$). $\Rightarrow$ Lower loads give higher T-E as long as C-E $\geq \sim 96.5\%$. 
At each speed, find highest efficiency point, using procedure on previous slide.
- Use Early-DI fueling with $T_{in} = 30^\circ C$.
- Increase fueling ($\phi_m$) to improve C-E and advance CA50 up to Ringing $\approx 5$.
  > Reached C-E $\sim 96.5\%$, 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 $\leq 5$.
- 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.
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 $\leq 5$ (CA50s similar).
  - Higher $\gamma$ increases efficiency.
- T-E is $\sim 0.4$ 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

Previous work, SAE 2011-01-0897

- Gasoline autoignition becomes sensitive to local $\phi$ with intake boost.
- Allows use of partial fuel stratification (PFS) to significantly reduce $\text{PRR}_{\text{max}}$:
  - Premix $\geq 80\%$ of fuel, late-DI for rest.
  - Higher loads for same CA50.
  - Advance CA50 for higher efficiency.

Recent Results with E10 ($C-E \geq 96\%$)

- PFS is also effective with E10 ($\sim 9\%$DI).
  - Higher T-E and higher load.
- Early-DI fueling, further increases T-E.
  - Mixture similar to PFS, and $T_{\text{in}}$ reduced to 30°C, less heat loss & higher $\gamma$.
- Example at $P_{\text{in}} = 2.8$ bar, const. fueling shows increased T-E with increasing PFS and early-DI with $T_{\text{in}} = 30$°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 $T_{in} = 60^\circ C$ collapse into a single band when plotted against CA50.
  - Appears to be reaching a max. at $\sim 365^\circ CA \Rightarrow$ reasonable with Heat-Transfer.

  - Compare with idealized curve $\Rightarrow$ agrees well. EGR effect in real data.

  - Little advantage to advancing CA50 beyond $\sim 368 - 370^\circ CA$.

  - 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.
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 \(P_{in} \geq \sim 2\) 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.

Side-view imaging shows bulk-gas & wall regions

Field of view

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.
Effects of $T_{\text{in}}$ and $T_{\text{coolant}}$ on TS

- TS increases with increasing $T_{\text{in}}$ ⇒ also with decreased $T_{\text{coolant}}$

- Expected that increased $\Delta T = T_{\text{bulk-gas}} - T_{\text{wall}}$ would increase TS.

- However, TS converges for CA $\geq 340^\circ$  
  - Mainly because TS curves for the higher $T_{\text{in}}$ (and greater $\Delta T$) begin to flatten.

- Possibly due to over mixing reducing the TS.  
  ⇒ Effect should be larger for larger $\Delta T$.

- 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 $> 330^\circ$ suggests mixing out bulk-gas faster than bringing in new cold gas.

- TS increases with increased $T_{\text{in}}$ & lower $T_{\text{coolant}}$, 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.