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.

**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

**Project objective:** 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.
  - FY09: 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 $\Rightarrow$ design well-characterized experiments to isolate specific aspects of HCCI/SCCI combustion & relationships between parameters.
  - Intake boost: Systematically increase boost $\Rightarrow$ 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 $\Rightarrow$ detailed investigations of in-cylinder processes.
  - Thermal stratification (TS): Develop temperature-imaging diagnostic $\Rightarrow$ Apply to obtain T-map images showing temporal and spatial development of TS.

- Computational Modeling $\Rightarrow$ 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.
• 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
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.

- 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.
    ⇒ 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.
Temporal Evolution of TS

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

• 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 $T_{\text{gas}} > T_{\text{wall}}$.
  – 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.
• Apply probability density functions (PDF) to quantify changes in temp. distribution with crank angle.
  — 305°CA: PDF very narrow.  
    > Little time for development of TS.  
    > Analysis ⇒ almost all width is shot noise.
  — 360 - 390°CA: 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).
- **330°CA**: bulk-gas temp. is nearly uniform. ⇒ Significant TS only for \( z/h \geq -0.43 \).
- **360°CA**: TS developed throughout bulk gas. ⇒ 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 ⇒ drops to \( T_{\text{wall}} \approx 400 \text{ K} \).
- BL thickness based on a 5% deficit from centerline value ⇒ 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 \( P_{in} > 160 \text{ kPa} \), \( T_{in} \rightarrow T_{amb} \) ⇒ limits allowable fueling.
- Add cooled EGR to further slow autoignition.
  - Achieved \( \text{IMEP}_g = 16.3 \text{ bar, } P_{in} = 324 \text{ kPa} \).
    - Very high \( \text{IMEP}_g \) for HCCI/LTC, convent’l fuel.
    - Near stoich., C/F = 38.5, EGR = 60%, \( P_{exhaust} = 326 \text{ kPa, } T_{exhaust} = 407°C \).
  - Ringing ≤ 5 MW/m², No Knocking.
  - Std-Dev of IMEP\(_g\) ≤ 1%, very good stability.
**Efficiency and NOx for Boosted High-Load**

For maximum IMEP<sub>g</sub> 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 \( P_{\text{in}} = 100 \), \( T_{\text{peak}} > 1900 \text{K} \).

- For max. IMEP<sub>g</sub> = 16.3 bar, \( P_{\text{in}} = 3.2 \) bar.
  - Ind. Thermal Eff. = 47%
  - Comb. Eff. = 99%
  - NOx = 0.015 g/kg-fuel, \( T_{\text{peak}} = 1750 \) 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°C
  - 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.
• Joint project with LLNL ⇒ spec. analysis. Sandia ⇒ engine op. & data interpretation.

• Conducted fueling(\(\phi\))-sweep & data for near-misfire conditions. Results provide:
  – Data for aftertreatment & model validation.
  – Improved understanding of combust. 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 ⇒ mechanism / enhancement.

• Additional ethanol studies over a wide range of operating parameters: EGR, load, & boost to high levels ⇒ 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. ⇒ 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 IMEP₉, 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.