HCCI and Stratified-Charge CI Engine Combustion Research

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DOE Merit Review Presentation
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Sponsor: U.S. DOE, Office of Vehicle Technologies
Program Manager: Gurpreet Singh

This presentation does not contain any proprietary or confidential information.

Purpose of Work

<u>Project purpose</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.

- HCCI has substantial advantages over traditional engines.
  - Compared to SI engines ⇒ fuel consumption reduced up to 30%.
  - Compared to Diesel ⇒ meet 2010 without lean-NO_X or PM aftertreatment, and with similar efficiency.
- Huge potential for reducing US petroleum consumption, 2 – 3 MBPD.
- HCCI engines can operate with alternative fuels ⇒ further reductions.
- HCCI engines are potentially lower cost than a diesel, with similar eff.
- Research is required to overcome the technical barriers.

Response to Previous Reviewer's Comments

- Reviewer's comments were generally very positive.
- No strong consensus on comments/suggestions.
  - Expressed importance of working with two-stage ignition fuels.
    - We will continue to include two-stage fuels in our investigations.
    - Conducting substantial work in this area under Aramco/Chevron-funded complementary project. ⇒ Results presented at AEC meetings & SAE.
  - Importance of VVA for studying NVO, etc. ⇒ System is now operational.
  - Importance of industrial interactions.
    - We are working to maintain/expand our interactions, but keep work broad enough to be valuable to all interested in HCCI & HCCI-like combustion.
    - Discussion of industrial interactions will be given later in Technology Transfer slide.

Technical Barriers

Our work in FY08 addresses the following barriers:

- Extend HCCI operating range to higher loads.
- Control HC and CO emissions at low loads.
- Improved understanding of fuel effects.
- Control of combustion phasing over the load/speed map.

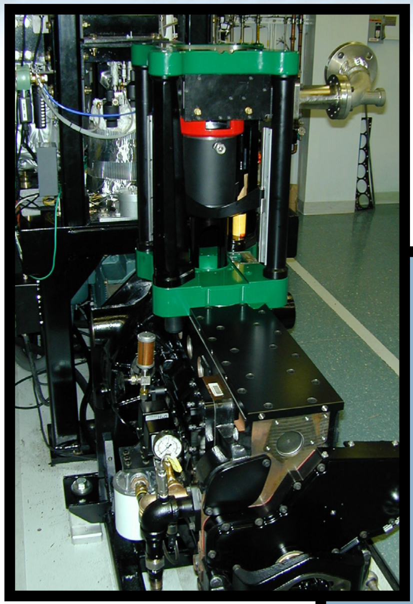
Approach

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

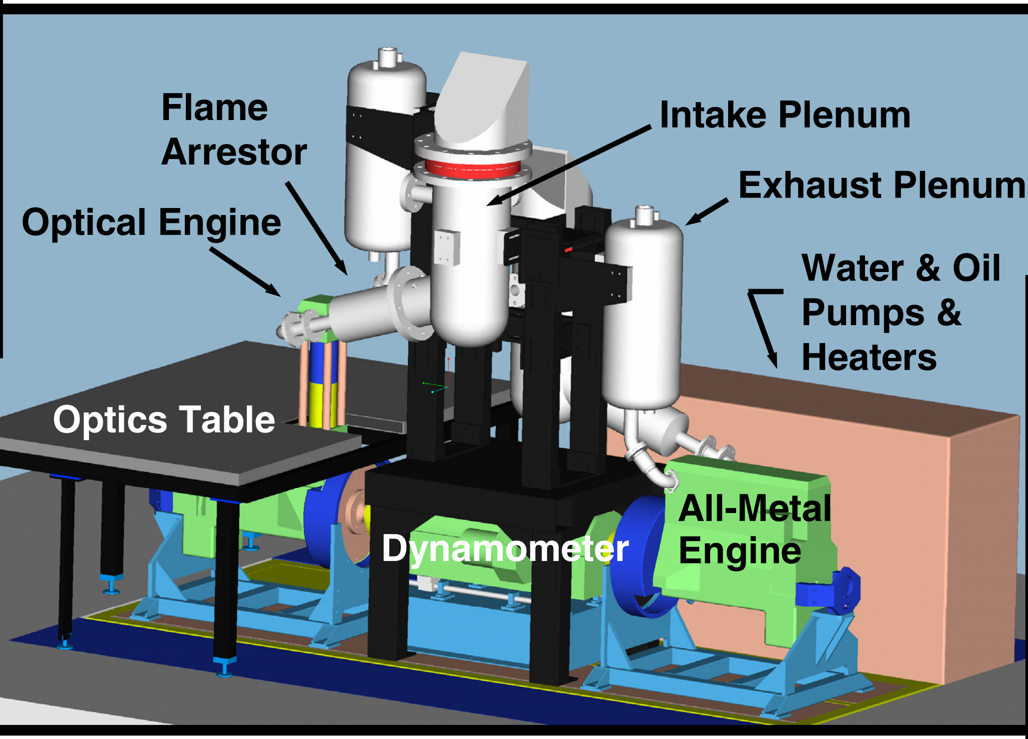
- Metal engine ⇒ design well-characterized experiments to isolate specific aspects of HCCI/SCCI combustion & relationships between parameters.
  - Many fundamentals are also relevant to HCCI-like diesel, *e.g.* EGR effects.
- Optical engine ⇒ detailed investigations of in-cylinder processes.
  - Laser-sheet imaging of temperature distribution.
- Computational Modeling ⇒ supplement experiments by showing cause-and-effect relationships that are not easily measured.
  - In-house CHEMKIN (Senkin) single- and multi-zone kinetic modeling.
  - Collaborate with LLNL & UW on full KIVA/multi-zone simulations.
- Combination of techniques provides a more complete understanding.
- Transfer results to industry.

Sandia HCCI / SCCI Engine Laboratory

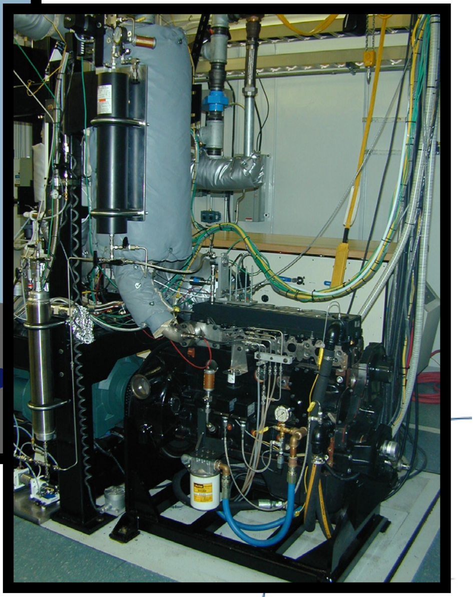
- Matching all-metal & optical HCCI research engines.
  - Single-cylinder conversion from Cummins B-series diesel.



Optical Engine



All-Metal Engine



- Cooled EGR loop added for current experiments.

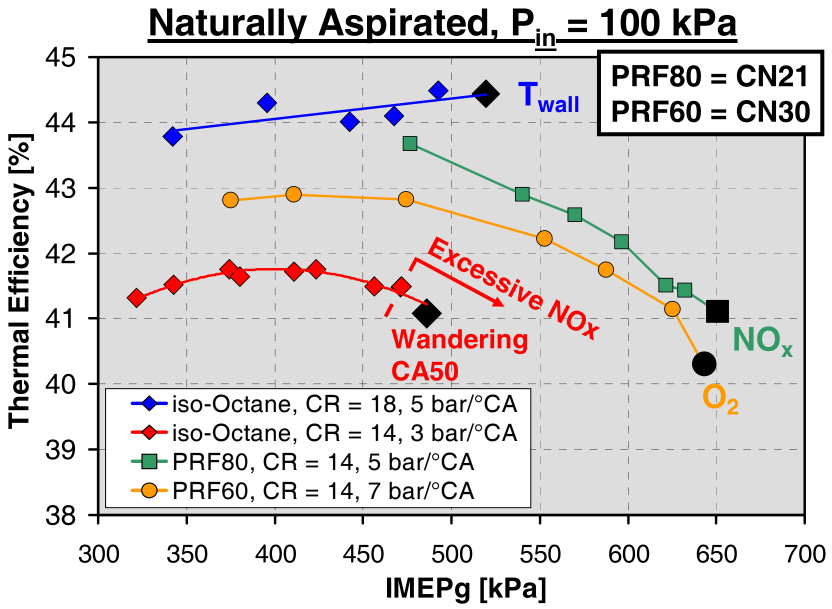
Technical Accomplishments – FY08

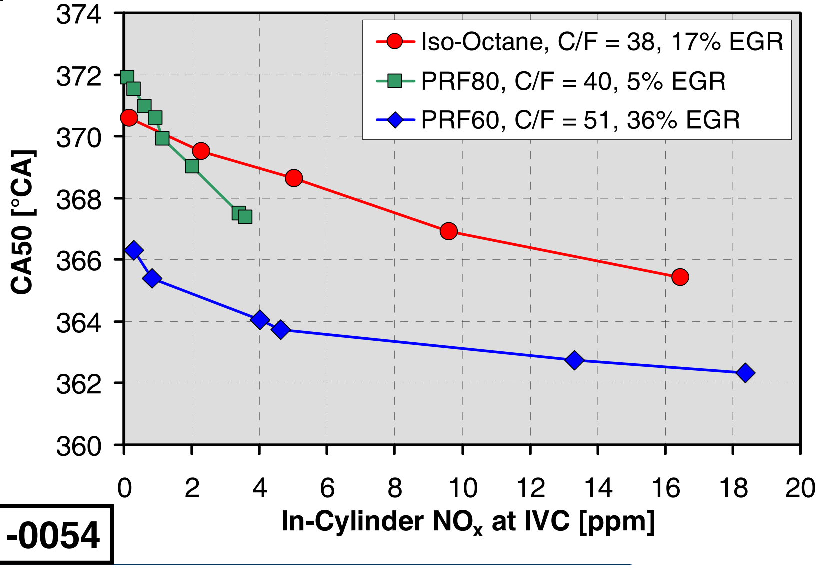
- Completed investigation of high-load limits for single- and two-stage fuels and identified three different mechanisms for these limits.
- Determined the effect of EGR/residuals on the HCCI heat-release rates and NO_X formation for well-mixed HCCI.
  - Isolated these effects from EGR effects on combustion phasing and IMEP.
- Initiated development of a planar temperature-measurement technique to determine the evolution of thermal stratification in an HCCI engine.
- Completed detailed exhaust-speciation analysis for iso-octane fueling. ➔Expanded study to include exhaust-speciation for gasoline fueling.
  - Project conducted in cooperation with LLNL.
- Completed VVA system – demonstrated NVO and late IVC operation.
- Supported chemical-kinetic and CFD modeling work at LLNL & UW.
  - Kinetic mechanisms $\Rightarrow$ improve pressure dependence, for various fuels.
  - CFD modeling $\Rightarrow$ better understand in-cyl. processes & emiss. formation.

High-Load Limits and Mechanisms

Single- and Two-Stage Ignition Fuels

- To prevent knock, combustion phasing must be retarded as fueling is increased.
- Iso-octane (1-stage ignit.) much more sensitive to changes in T_{in} at high retard.
  - Wall-heating feedback limits CA50 control at IMEPg = 486 or 520 kPa.
  - CR=14, NO_X > 2010 limits.
- PRF80 & PRF60 (2-stage), less sensitive to T_{in}, allows greater retard & higher IMEP.
  - NO_X < 2010 limits, because T_{in} is lower, so lower peak temp. and more induced mass.
- PRF80 limited to IMEPg = 650 kPa, due to NO_X feedback runaway.
- PRF60 limited to IMEPg = 640 kPa, due to insufficient O_2, because of high EGR levels required to maintain phasing retard.

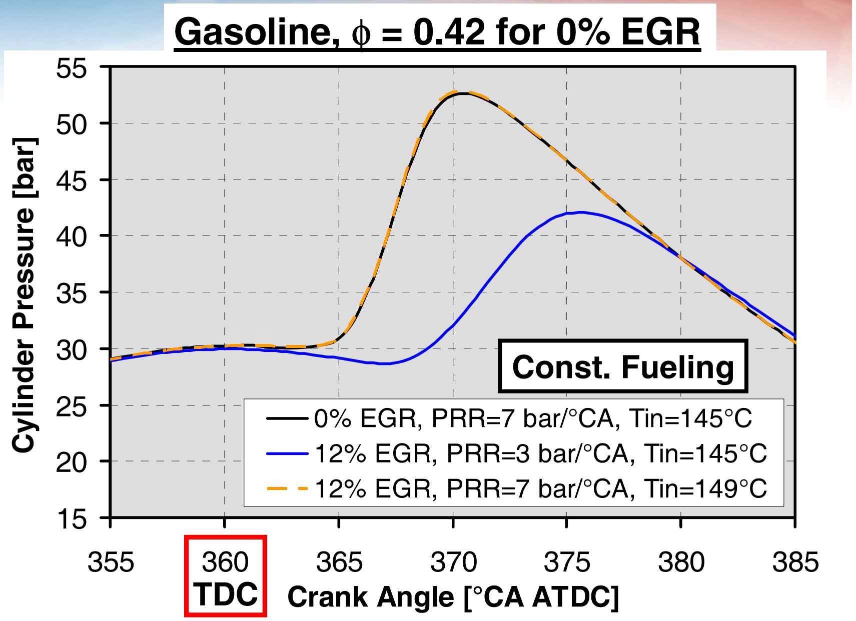


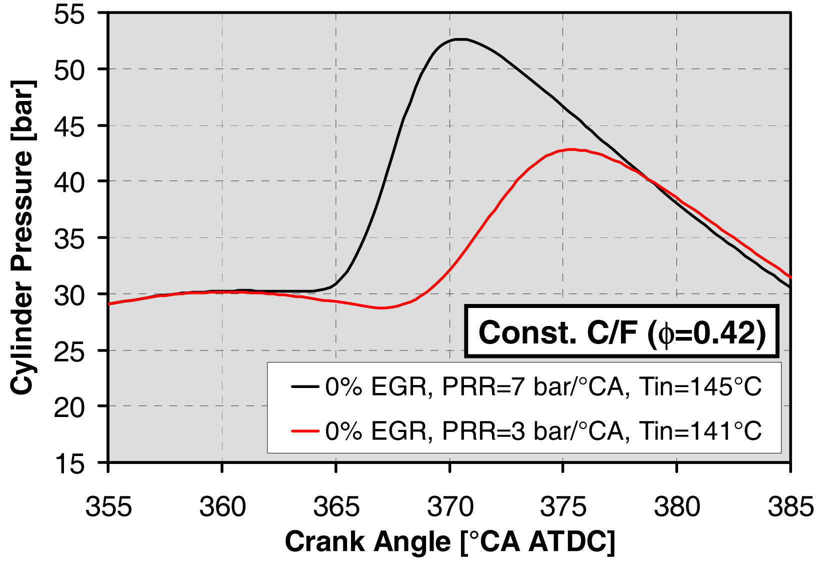


Details in SAE 2008-01-0054

Effects of EGR/Residuals on HCCI Heat-Release Rate (HRR) and NO_X Formation

- Can EGR help to avoid load-limit factors on previous slide? ⇒ Reduce knock and NO_X with less timing retard.
  - Knock results from excessive PRR/HRR.
- Previous works have suggested that EGR is effective for reducing the HRR and NO_X formation (peak temps.).
- However, results not conclusive since other effects of EGR were not controlled.
  - **Combustion phasing** (CA50) & **IMEP**.
- EGR retards CA50, which slows PRR.
  - Similar results obtained with reduced T_{in}.
- With phasing control, the effect on HRR is unclear for low EGR levels (12%).
- Conducted well-controlled experiments over wide range of EGR levels.

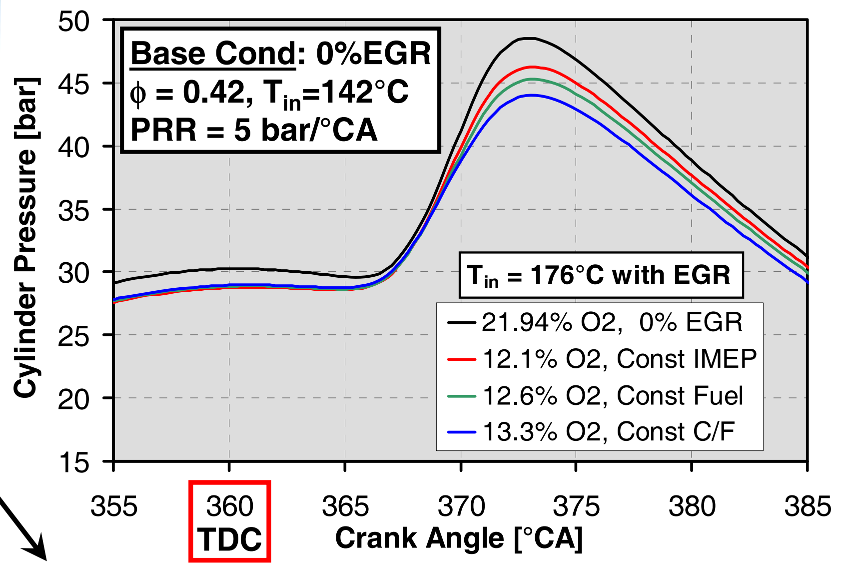


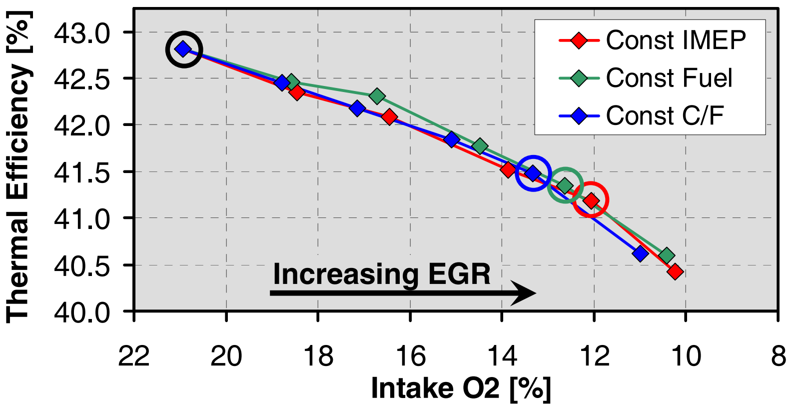


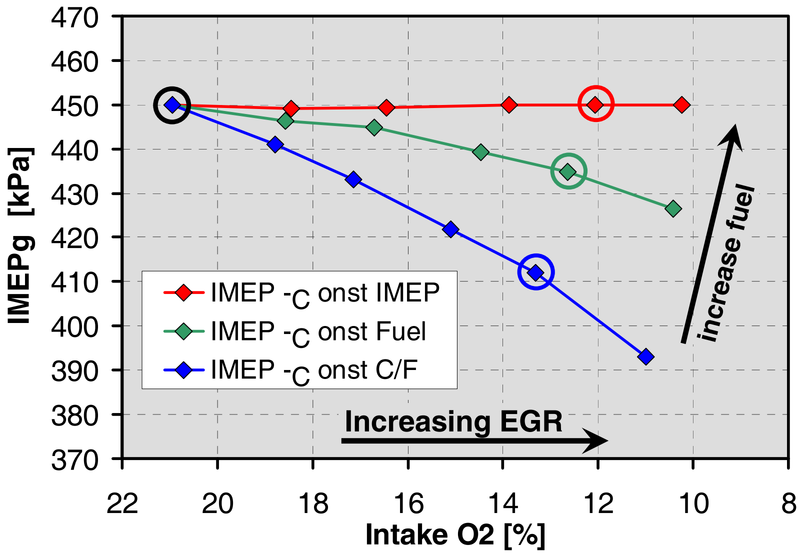
Effects of EGR on IMEP and Thermal Efficiency

- Maintain constant CA50 = 370°CA by increasing T_{in} as EGR is added.
- Plot shows ~47% EGR ⇒ T_{in} was increased from 142°C to 176°C.
- Higher T_{in} reduces charge mass.
  - Same C/F ratio gives lower IMEP.
  - Constant fueling also gives lower IMEP.
- Must increase fueling to maintain constant IMEP with EGR addition.
  - Lower γ (c_p/c_v) with EGR reduces $\eta_{thermal}$

Gasoline, CA50 = 370°CA

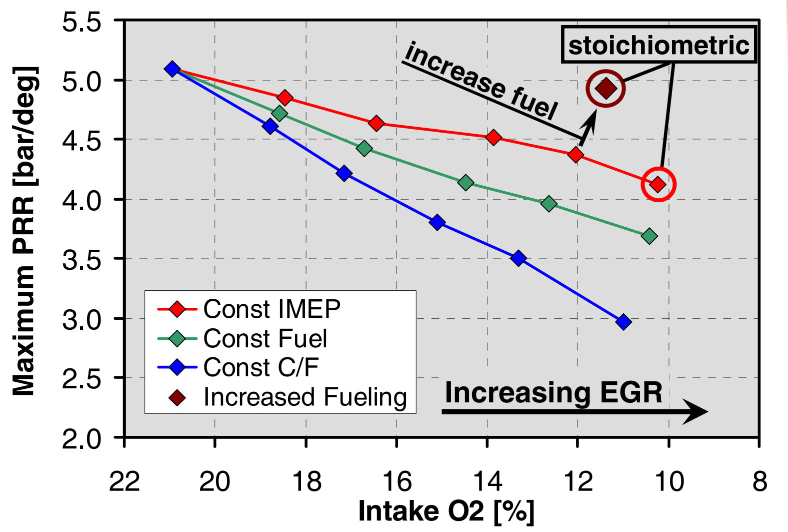


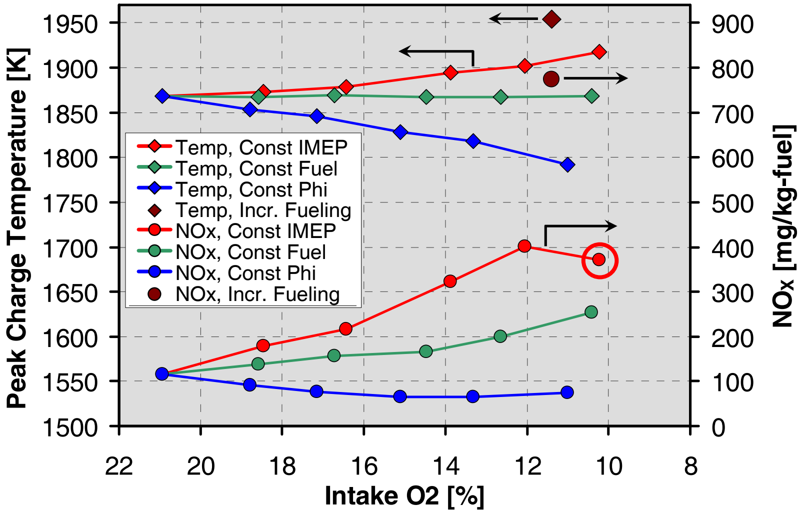




Effects of EGR on PRR and NO$_X$

- Max. PRR for constant IMEP reduced slightly from 5 to 4.5 bar/deg with EGR. ⇒ Incr. IMEP 450 to 475 kPa, same PRR.
- Very small benefit. ⇒ Similar result achieved by retarding CA50 only 1°CA.
- Loss of thermal eff. ~2% using EGR compared to ~0.1% for retard.
- Peak temperatures and NO$_X$ increase!
  - Higher T_{in} and higher required fueling.
  - Slightly less increase as approach stoich.

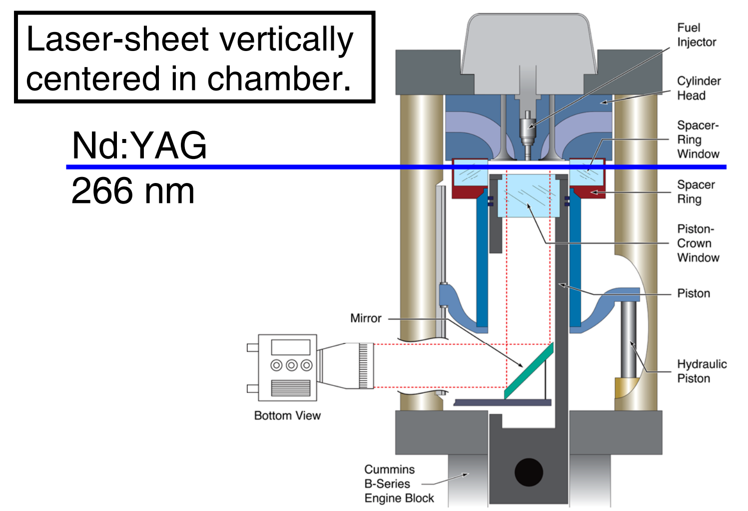




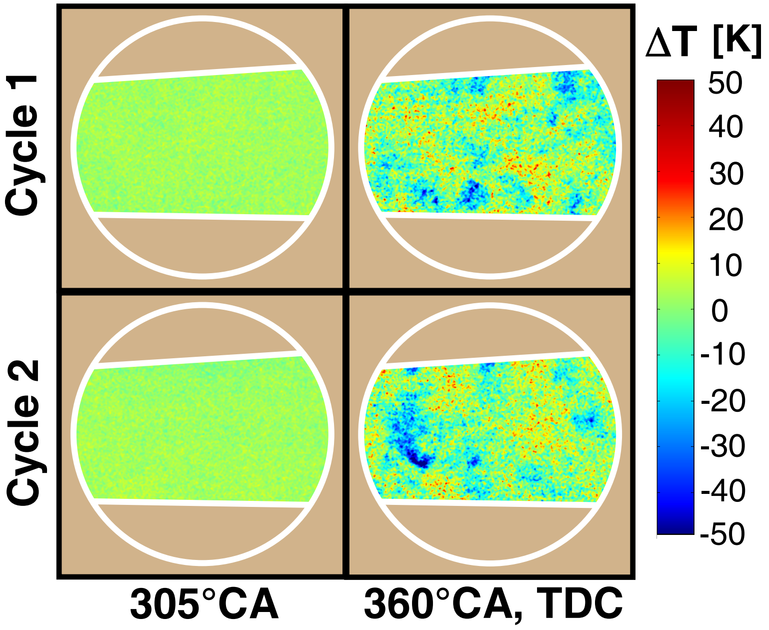
- EGR gives minimal direct benefit for PRR & is detrimental for η_{th} & NO$_X$ at cond. st'd.
- However, often needed for ignit. control and allows stoich. op. ⇒ 3-way catalyst.
- Limits peak temps. for SCCI/PCCI comb.

Planar Temperature Measurements

- Thermal stratification (TS) is essential for HCCI operation at all but the lowest loads.
  - Amplify effect with timing retard for high load.
- Previous work ⇒ TS caused by convection of cooler near-wall gases into bulk gas.
- Increasing TS has strong potential for extending high-load limit of HCCI.
- Measuring in-cyl. temperatures is critical for understanding TS, and ways to increase it.
- PLIF of toluene tracer is temp. sensitive.
  - For well-mixed fueling, variations in PLIF intensity correspond to variations in temp.
  - Calibrate temp. sensitivity in-cylinder.
- Preliminary images very promising ⇒ detect increase of TS from 305° to 360°CA.
- Studies of development of TS are planned.

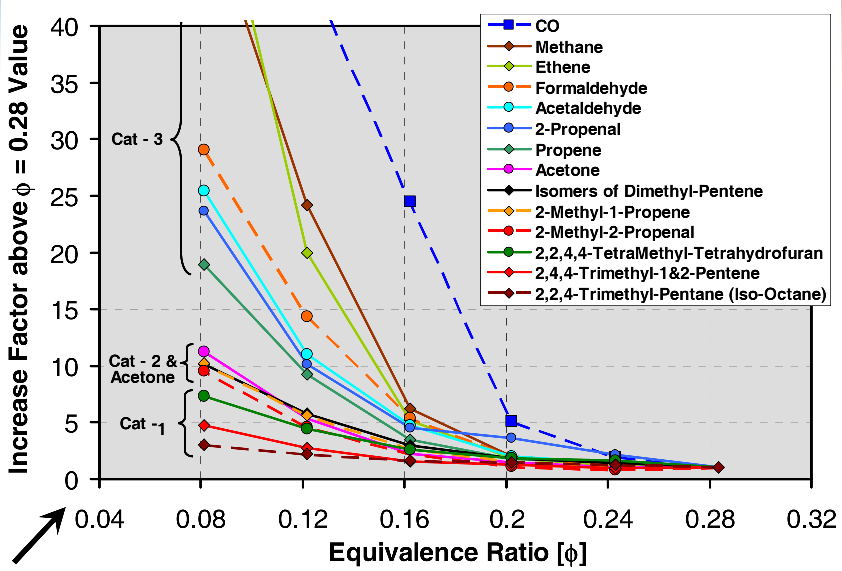


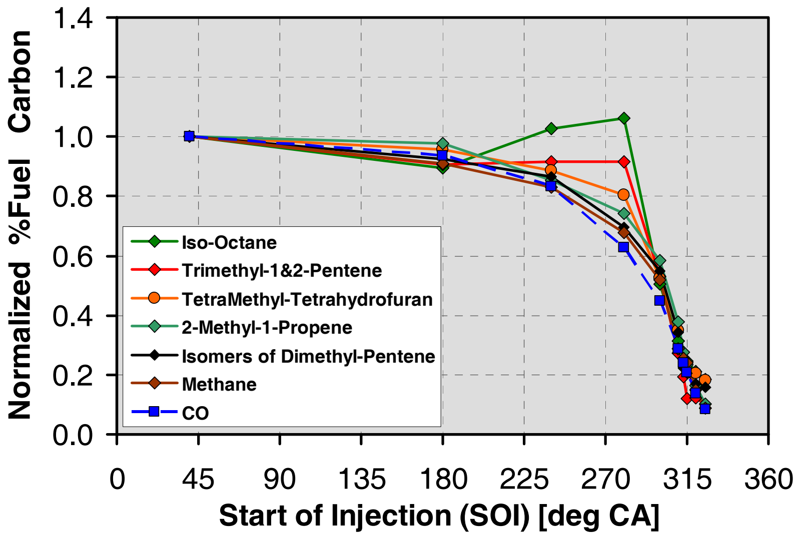
Laser-sheet vertically centered in chamber.



Detailed Exhaust Speciation – Iso-Octane and Gasoline

- Joint project with LLNL. ⇒ They will discuss gas-spec. analysis techniques.
- Fueling- and stratification(SOI)-sweeps show similar trends for both fuels.
  - Confirms significant OHC in emissions. (formaldehyde, acetaldehyde, acetone, etc.)
  - Unreacted fuel most significant HC spec.
- Normalized data shows progression from: fuel → break-down prod. → small spec. → CO.
  - Explained by in-cyl. temp. distribution.
  - Indicates where various species form in-cyl.
- SOI-sweep indicates two reasons for improved low-load η_{comb} with stratification.
  - Locally richer regions burn more completely.
  - Reduced mixing time removes fuel from crevice and colder near-wall regions.



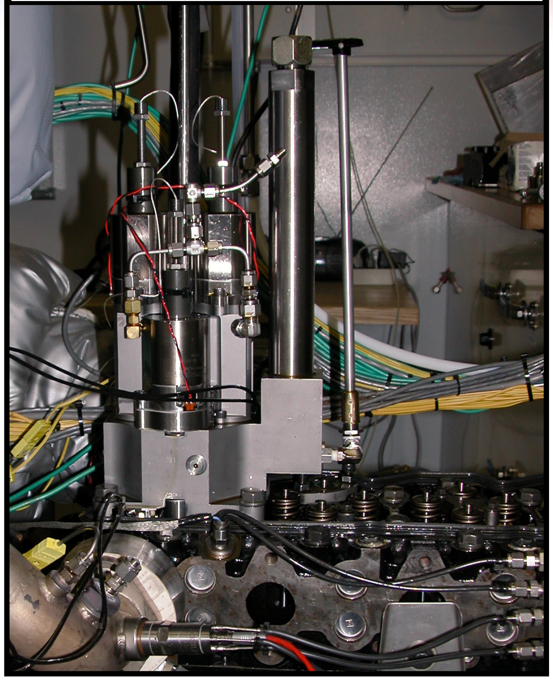


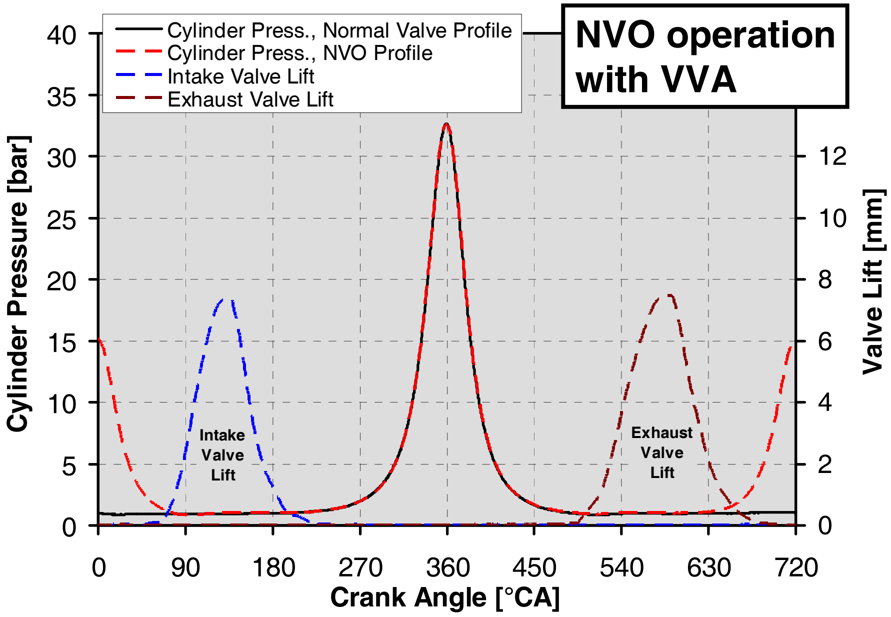
Details in SAE 2008-01-0053

VVA System is Operational

- Electro-hydraulic VVA is fully flexible.
  - Control of valve timing, duration, and lift.
- Design by International Truck & Engine Co., adapted to fit our engine.
  - In-house developed electronics and software.
- VVA build complete. ⇒ Verified VVA capability for late IVC and NVO operation on motored engine.

VVA on engine, cover removed





NVO operation with VVA

- Allows investigation of exhaust rebreathe and NVO, vs. heated T_{in}.
  - Strong interest by auto companies.
- Late IVC allows variation of effective CR for ctrl., & high-CN fuels (D2-like).

Technology Transfer / Interactions

- Project is conducted in close cooperation with U.S. Industry through the Advanced Engine Combustion (AEC) Working Group.
  ⇒ Discussion and feedback incorporated into work.
  - <u>OEM Partners</u>: Caterpillar, Chrysler, Cummins, Detroit Diesel, Ford, GE, GM, International, John Deere, and Mack-Volvo.
  - <u>Energy Co. Partners</u>: BP, Chevron, ConocoPhillips, ExxonMobil, and Shell.
  - <u>National Lab. & Univ.</u>: SNL, LANL, LLNL, ANL, and U. Wisconsin.
- Participate in meetings of the University HCCI Consortia (UM & UW).
- <u>GM</u>: In-depth discussions on gasoline HCCI. ⇒ Led to current EGR-HRR study. Suggested future work on exhaust-rebreathe HCCI & thermal strat.
- <u>International Truck & Engine Co</u>: Development of VVA system. Discussions to provide guidance and review of their diesel-HCCI project.
- <u>Saudi-Aramco</u>: Funding complementary project on advanced HCCI fuels. <u>Chevron</u>: Joined Aramco project as equal partner (3-yr contract in place).
- <u>LLNL & Universities</u>: Cooperative modeling, diagnostic, & emiss. projects.
  ⇒ Details on next slide.

Interactions with LLNL and Universities

- LLNL: 1) Support chemical-kinetic mechanism development, Pitz *et al*.
  2) Cooperative project for detailed exhaust speciation, Davisson *et al.*
- LLNL and Univ. of Wisconsin: Cooperative Project on CFD modeling of in-cylinder processes and emissions formation, Aceves *et al.* LLNL, Hessel and Foster, UW.
- Stanford: Advanced two-laser optical diagnostic for planar for in-cylinder temperature and mixture measurements, with R. Steeper, SNL (Hansen *et al.*, Stanford).
- Univ. of Wisconsin – Milwaukee: Data for modeling effort.
- Univ. of New South Wales, Australia: Discussions regarding potential collaboration on modeling of ethanol-fueled HCCI.

Plans for Next Fiscal Year

- Complete investigation of the effects of EGR/residuals on HRR and NO_X, by extending operation to the high-load limit of HCCI.
  - Can higher IMEP be reached with EGR at T_{wall} control limit? ($\eta_{thermal}$ and NO_X?)
  - Future direction: investigate benefits of EGR for boosted operation.
- Investigate development of thermal stratification through the cycle using current single-laser planar temperature technique (bulk-gas and BL).
  - Future direction: extend to other op. cond., *e.g.* variations in speed, piston geom.
  - Future direction: compare with Stanford 2-laser tech. & apply to high-resid. cond.
- Apply VVA to compare HRR and performance for exhaust rebreathe, NVO, and heated T_{in}. ⇒ Understand effects on thermal stratification & load limits.
  - Future direction: Initial focus on exhaust rebreathe, based on disc. with OEMs.
- Investigate Ethanol ⇒ effects of load, speed, EGR, and other parameters.
  - Future direction: mixture-stratified operation with ethanol (other renewable fuels).
- Detailed exhaust speciation under near-misfire conds. for 1- & 2-stage fuels.
- Continue to collaborate with LLNL on improving chemical-kinetic mechanisms and on CFD/kinetic modeling.

Summary and Conclusions

- Three mechanisms identified that limit high-load HCCI operation for various fuels/conditions: 1) wall-heating feedback ⇒ thermal runaway, 2) NO_X feedback runaway, and 3) limited O_2 due to high EGR.
- EGR gives little direct benefit for slowing HRR and reduces $\eta_{thermal}$ ~2%.
  - Similar benefit achieved by retarding CA50 only 1°CA, reduces $\eta_{thermal}$ ~0.1%.
- For well-mixed operation, EGR results in **higher** NO_X for same IMEP.
  - However, stoichiometric operation with high EGR allows use of 3-way catalyst.
- Developed planar temperature-measurement technique ⇒ based on PLIF imaging of fuel-tracer, calibrated in-cylinder.
  - Demonstrated measurement of thermal stratification.
- Detailed exhaust speciation study for iso-octane and gasoline.
  - Identified main HC & OHC species, and likely in-cyl. location for their formation.
- VVA system is operational – demonstrated NVO and late IVC operation.

Publications, etc.

1. Hwang, W., Dec, J. E. and Sjöberg, M., "Fuel Stratification for Low-Load Combustion: Performance & Fuel-PLIF Measurements," SAE paper 2007-01-4130, accepted for *SAE Transactions*, presented at SAE Powertrain and Fluid Systems Conference, Oct. 29-Nov. 1, 2007.
2. Hwang, W., Dec, J. E., and Sjöberg, M., "Spectroscopic and Chemical-Kinetic Analysis of the Phases of HCCI Autoignition and Combustion for Single- and Two-Stage Ignition Fuels," accepted *Combustion and Flame*, Jan. 2008.
3. Dec, J. E., Davisson, M. L., Leif, R. N., Sjöberg, M., Hwang, W., "Detailed HCCI Exhaust Speciation and the Sources of Hydrocarbon and Oxygenated Hydrocarbon Emissions," SAE paper no. 2008-01-0053, 2008 SAE Int'l. Congress.
4. Sjöberg, M. and Dec, J. E., "Influence of Fuel Autoignition Reactivity on the High-Load Limits of HCCI Engines," SAE paper 2008-01-0054, 2008 SAE International Congress, April 2008.
5. Silke, E., Pitz, W. J., Westbrook, C. K., Sjöberg, M., and Dec, J. E., "Understanding the Chemical Effects of Increased Boost Pressure under HCCI Conditions," SAE paper 2008-01-0019, SAE Int'l. Congress, April 2008.
6. Hessel, R. P., Foster, D. E., Aceves, S. M., Davisson, M. L., Espinosa-Loza, F., Flowers, D. L., Pitz, W. J., Dec, J. E., Sjöberg, M., Babajimopoulos, A., "Modeling Iso-octane HCCI using CFD with Multi-Zone Detailed Chemistry; Comparison to Detailed Speciation Data over a Range of Lean Equivalence Ratios," SAE paper 2008-01-0047, 2008 SAE International Congress, April 2008.
7. Dec, J., Sjöberg, M., and Hwang, W., " The Effects of EGR and Its Constituents on the Autoignition of Single- and Two-Stage Fuels," 13th Diesel Engine-Efficiency and Emissions Research (DEER) Conference, Aug. 13-16, 2007.

Invited Presentations

- Dec, J., Hwang, W, and Sjöberg, M., "Fuel Stratification to Improve Low-Load HCCI: Engine Performance & Fuel-PLIF Imaging," SAE International HCCI Symposium, Lund, Sweden, September 2007.
- Plenary Lecture: Dec, J. E., "Advantages of Charge Stratification in HCCI Engines," ICE2007 8th International Conference on Engines for Automobiles, SAE/NA-Naples Section, Naples, Italy, September 16-20, 2007.