Advanced Lean-Burn DI Spark Ignition Fuels Research

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Overview

Timeline

- Project start date: 2008 Jan
- Project provides fundamental research to support DOE/industry advanced lean-burn SI engine development for alternative fuels.
- Project directions and continuation are reviewed annually.

Barriers

- Inadequate understanding of advanced, highly boosted, direct-injection stratified-charge spark-ignition engines:
  - Robust (w/o misfires) lean-burn combustion technology.
  - Incomplete understanding of the dynamics of fuel-air mixture preparation / ignition.
  - Ethanol's lower AFR requires larger injected fuel mass, which influences fuel stratification.

Budget

- Project funded by DOE/VT.
- FY08 - $630 K.
- FY09 - $600 K.

Partners / Collaborators

- Project lead: Sandia (M. Sjöberg)
- 15 Industry partners in the Advanced Engine Combustion MOU.
- General Motors.
- HCCI Fundamentals Lab at Sandia (J. Dec).
- LLNL (W. Pitz) & Univ. of Galway (H. Curran).

Objectives for FY2009

Project goals are to provide the science-base needed to understand:

1. How emerging future fuels will impact the new, highly-efficient DISI light-duty engines currently being developed.
2. How engine design can be optimized to make the most efficient use of future fuels.

- Focus for the first years is on ethanol / gasoline blends.

Objectives for FY2009:

A) Build a future fuels lab for advanced lean-burn DISI engines.

- Design an optically-accessible DISI research engine.
- Install and commission the engine in the future fuels lab.

B) Evaluate ethanol for SI and HCCI operation, utilizing HCCI fundamentals lab.

- Determine the autoignition characteristics of ethanol over a range of loads, speeds, and intake-pressure boost .
- Evaluate the latest ethanol chemical-kinetics mechanism from LLNL.

FY2008-2009 Milestones

- Complete the design/modification of the optical head for the new light-duty fuels research engine. (September 2008)
- Complete new future fuels research laboratory infrastructure. (March 2009)
- Complete assessment of intake boost on ethanol HCCI autoignition. (June 2009)
- Finalize light-duty DISI engine installation to allow initial performance testing. (September 2009)

Approach

Lab and engine build-up:

- Base the engine lab and engine hardware off existing Sandia engine labs and optical engines, and improve to accommodate the unique requirements of advanced DISI engine fuels research.
- Collaborate with GM to acquire latest generation single-cylinder research cylinder head.
  - Spray-guided stratified charge SI combustion system.
  - Optical access to pent-roof combustion chamber.
  - Suitable fuel injectors, and high-energy ignition system.

Research:

- First, conduct performance testing with all-metal engine configuration over wide ranges of operating conditions and alternative fuel blends.
  - Speed, load, boost, EGR, and stratification level.
- Second, apply optical diagnostics to develop the understanding needed to improve operating conditions that show less-than-desired robustness, performance, or efficiency.

Supporting modeling:

- Conduct chemical-kinetics modeling of flame-speed and autoignition for detailed knowledge of governing fundamentals.
  - Perform validation experiment in HCCI fundamentals lab.
- Develop collaboration with DISI CFD modeling teams.

Technical Accomplishments

Future fuels DISI lab:

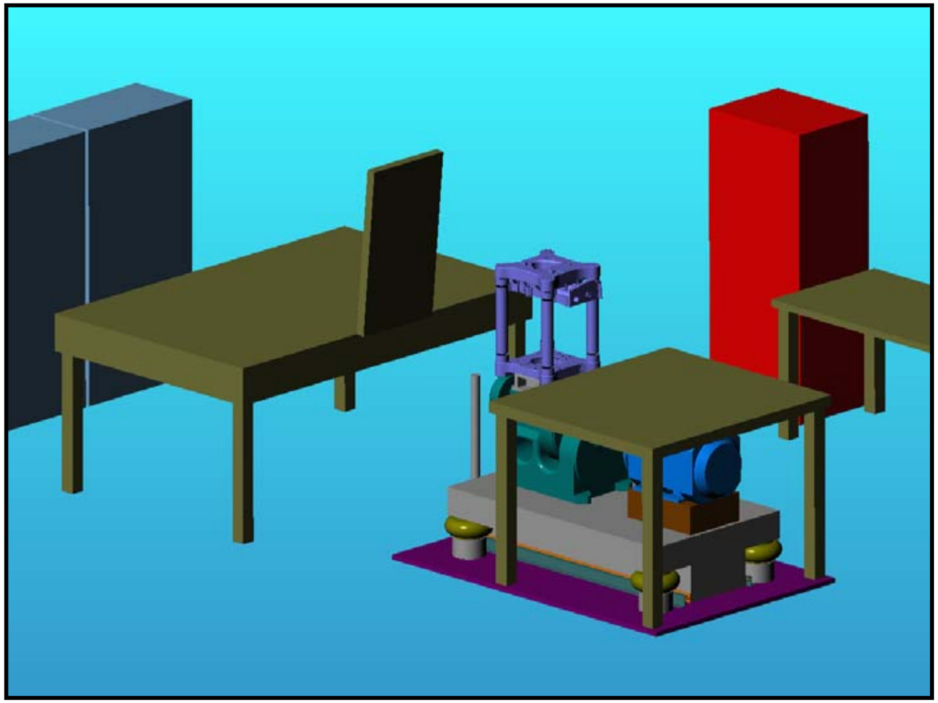
- Finished designing the laboratory room that houses new DISI research engine.
  - All room infrastructure has been finalized.
- Designed and installed an engine test stand with excellent vibration isolation.
  - High-performance AC induction motor for controlling engine speed and absorb load.
- Crank case of existing CLR research engine has been modified to accommodate new optical setup with extended-piston arrangement.
  - Modified balancing shafts and added Tungsten weights to ensure a well-balanced single-cylinder engine.
- Completed preliminary design of combined all-metal / optical engine.
  - Detailed design and manufacturing of parts is currently in progress.

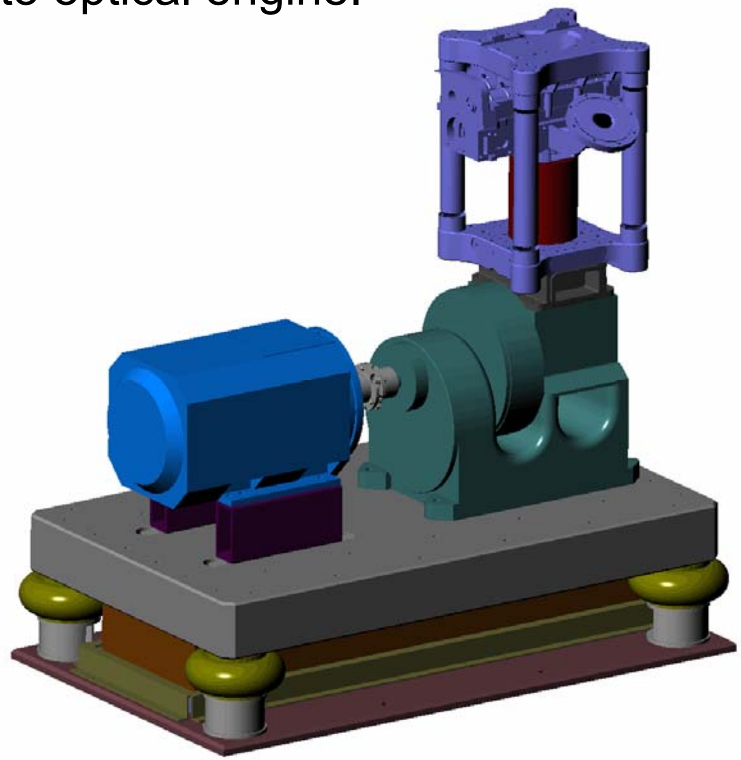
Initial fuel evaluation for DISI operation:

- Performed tests in the HCCI lab to assess ethanol and gasoline autoignition characteristics (as related to knock and flame speed for SI).
  - Compared results with PRF and other alternative fuel.
- Evaluated latest ethanol chemical-kinetics mechanism from LLNL.
  - Engine-speed and intake-boost sensitivity.

Lab Design

- Designed an engine-test stand based on an assembly of heavy steel plates suspended on AirMounts.
  - 2700 kg and natural frequency of 2.8 Hz prevent engine vibration from reaching sensitive lasers and other measurement devices.
- Improved access to engine by separating main laser table from engine.
  - Will use hinged optical bridge to link lasers to optical engine.





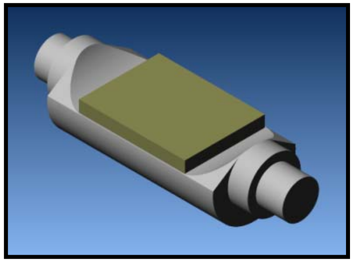
Laboratory Room

- Laboratory room is now essentially finished.
  - Electrical supply, ventilation, cable trays, shelves over engine and laser table.
- High-performance electric motor is installed.
  - 200 Nm steady-state, corresponds to 45 bar BMEP for this 0.55 liter engine.
- Variable-frequency drive is installed, 55 kW.

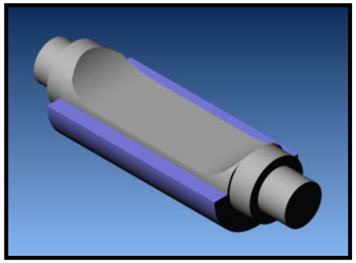
Engine Balancing

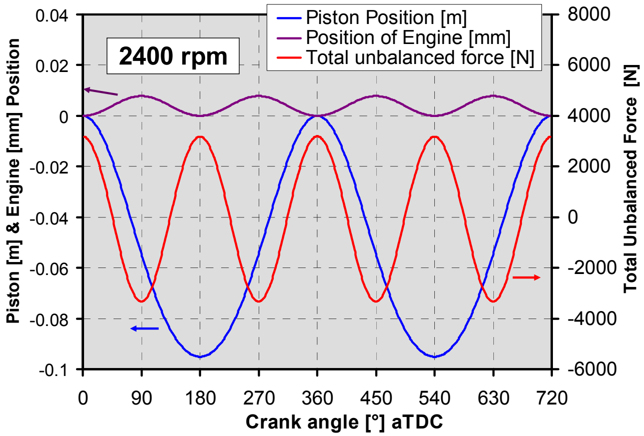
- Single-cylinder engine needs dynamic balancing of reciprocating masses.
- Redesign the current two counter-rotating balancing shafts to account for extra weight of extended optical piston.
- Existing connecting rod allows for up to 2.4 kg to be added to current CLR piston for operation up to 2400 rpm.
  - Will allow sturdy design of extended piston, for steady-state operation with 100 bar peak pressure.
- Tungsten addition to current balancing shafts can easily provide completely balancing of 1st order forces, as is custom.
- Computations show small total engine motion amplitude of 0.008 mm due to residual 2nd, 3rd… order forces.
- Tungsten HD17 Alloy was chosen for good machinability.

Original

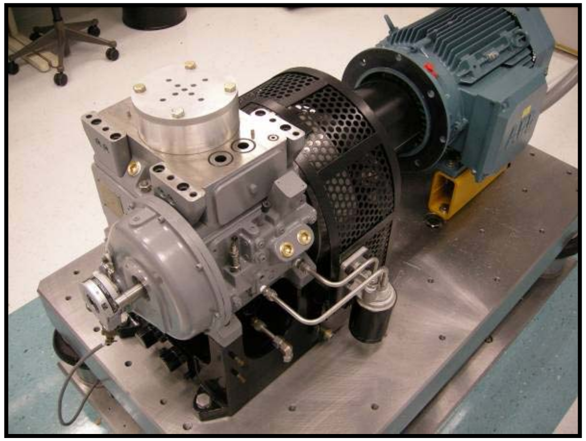


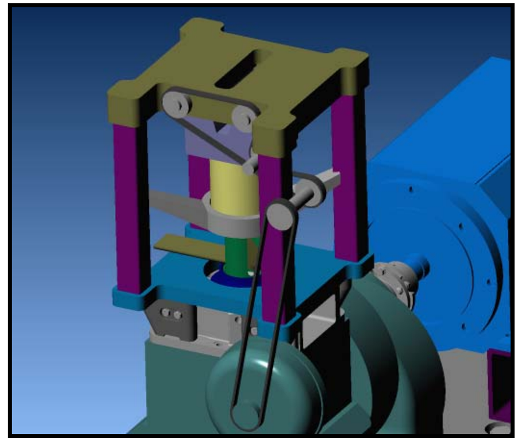
New with Tungsten

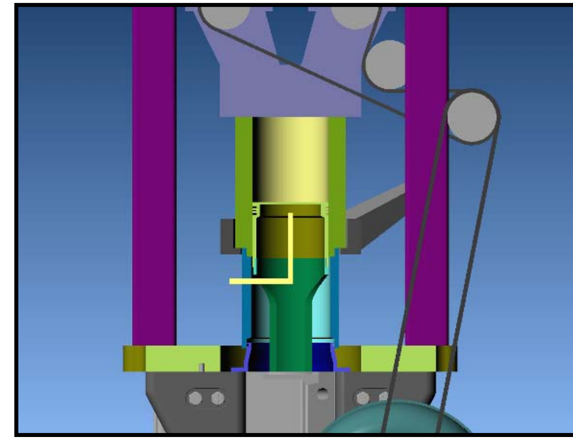


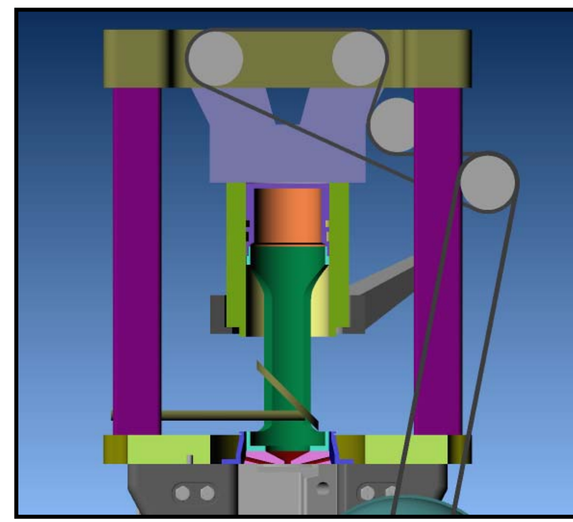


Research Engine Layout









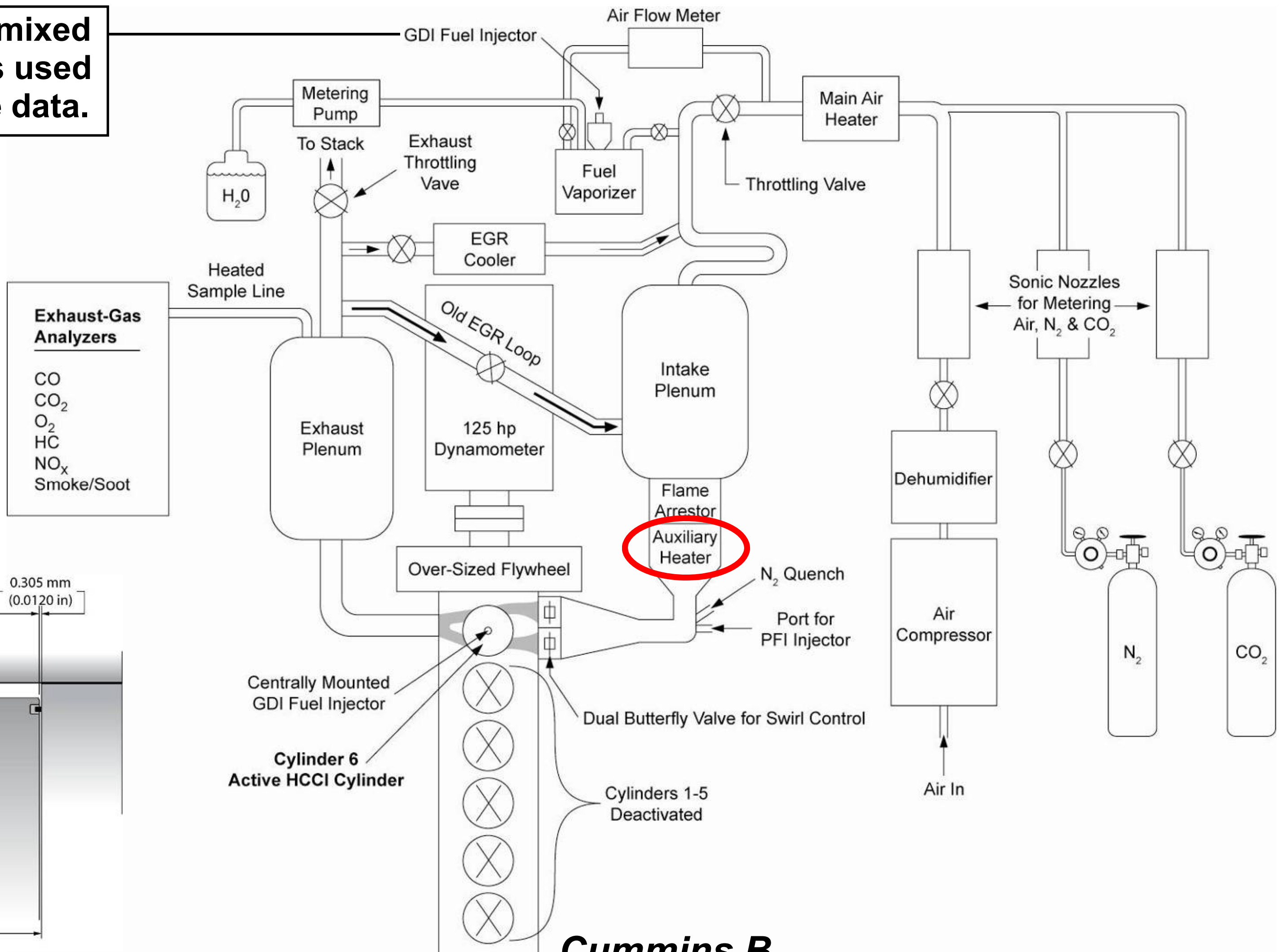
- Base of engine is ready.
- Bore 86mm x Stroke 95mm = 0.55 liter swept volume.
- Design and manufacturing of upper portion of engine is in progress.
- Two configurations:
- <u>One all-metal version</u> with metal-ring pack and oil cooling of piston (incl. lower cylinder for oil control).
- <u>One optical version</u> with pent-roof windows, piston top window, 45 mirror, spacer-ring windows, and endoscope access.
- Fuel PLIF, PIV, chemiluminescence imaging.

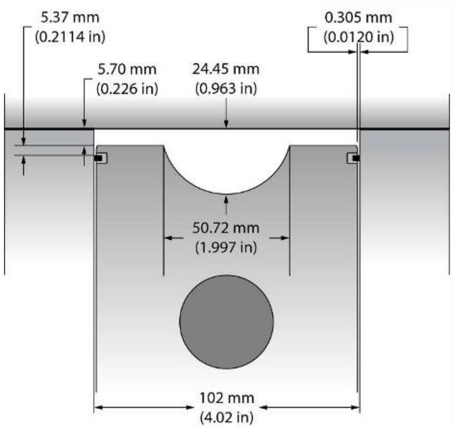
Fuel Evaluation for DISI Research

- The first fuels to be examined in the new DISI research engine are gasoline and ethanol, and various blends of the two.
- Since engine knock must be avoided when operating with alternative fuels, it is valuable to examine the autoignition characteristics of these fuels.
- Consequently, perform experiments in the HCCI fundamentals lab to assess gasoline, and especially, ethanol autoignition characteristics over a wide range of conditions.
  – Engine speed (performed to date).
  – Intake boost pressure (initial tests performed).
  – Fuel/air equivalence ratio – ϕ (initial tests performed, not shown here).
  – Charge temperature (future tests).
  – EGR rate (future tests).
- Compare autoignition characteristics of gasoline and ethanol with reference fuels.
- Evaluate the fidelity of existing chemical-kinetics mechanisms.
  – Can be used for modeling of both knock onset and flame speed.

All-metal HCCI Engine

Only premixed fueling is used for these data.



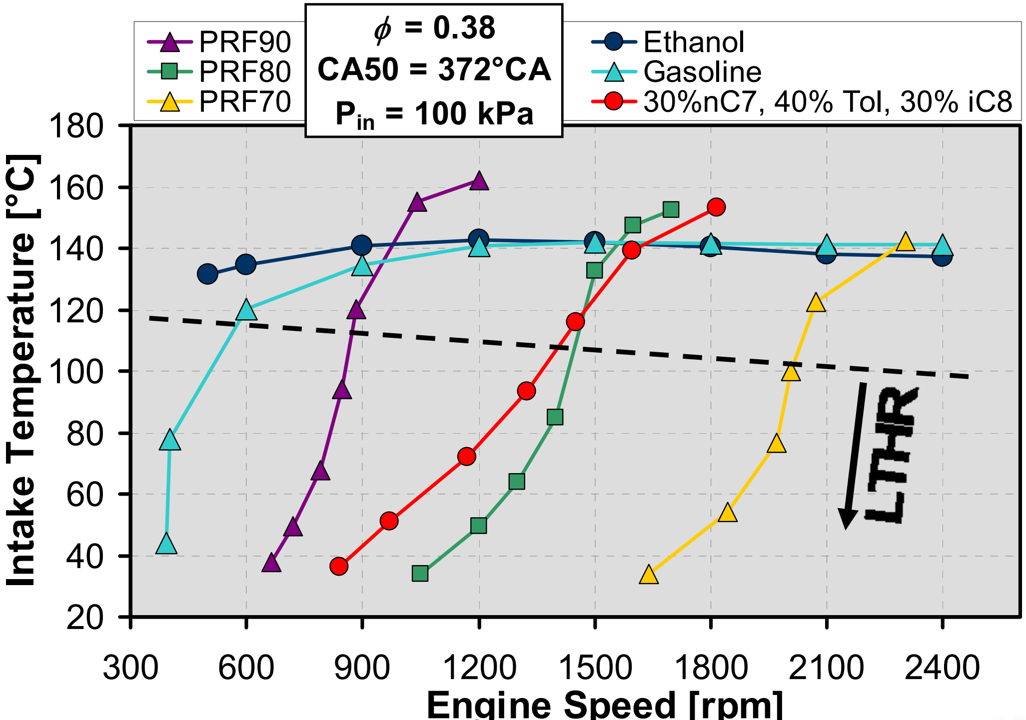


CR = 14

Cummins B
0.98 liter / cyl.

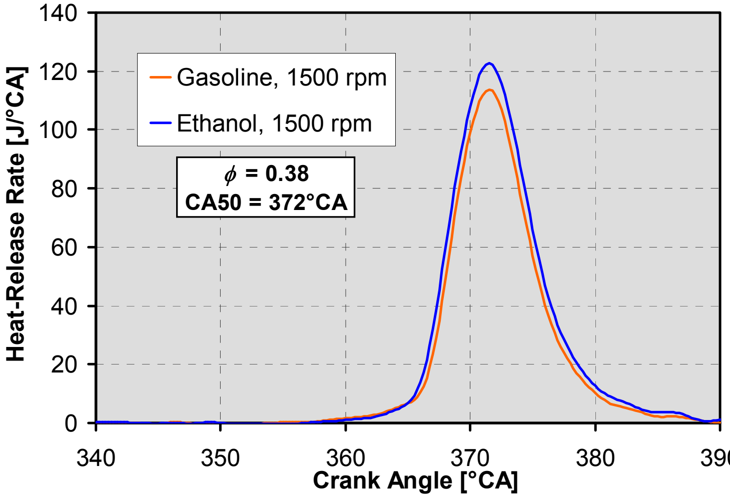
Engine-speed Sweep

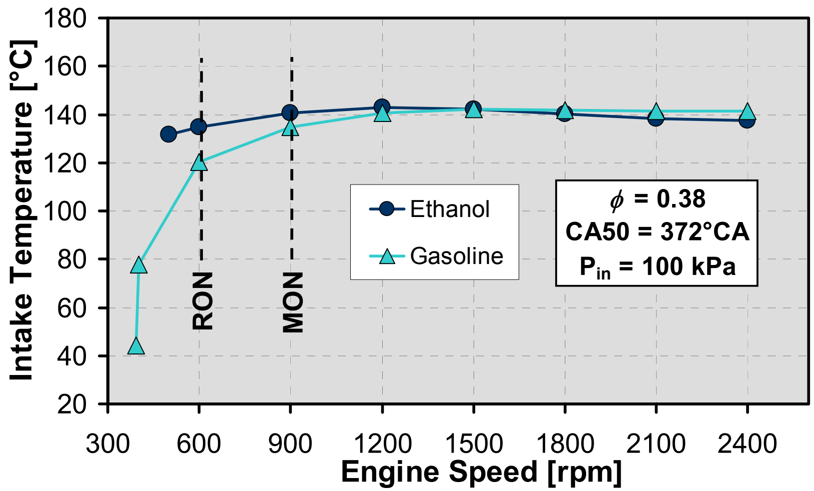
- Adjust the intake temperature (T_{in}) to maintain CA50 = 372°CA as engine speed is changed. (P_{in} = 100 kPa, simulating naturally aspirated oper.)
- The ensuing curve reveals a great deal about the autoignition characteristics of the fuel.
- In general, T_{in} < 110°C means that the fuel is exhibiting low-temperature heat release (LTHR), *i.e.* coolflames.
- The more reactive fuels (*i.e.* lower octane number) show LTHR for higher rpm.
- Ethanol is the only true single-stage ignition fuel.
  - No LTHR even for low T_{in} at 300 rpm (not plotted because no ignition).

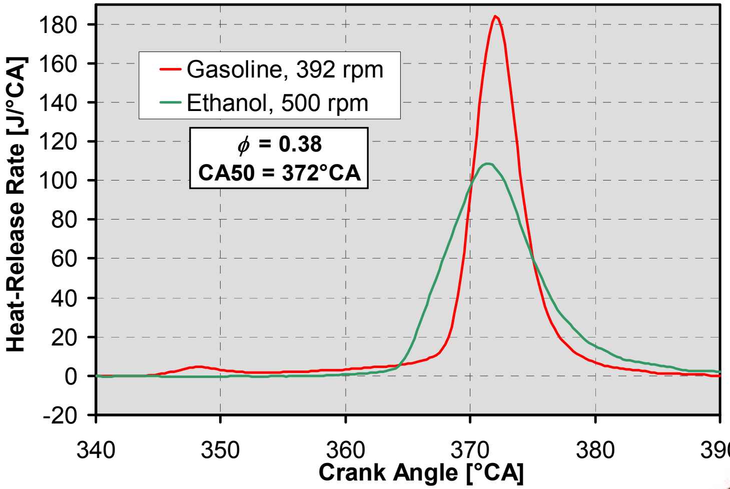


Gasoline vs. Ethanol

- The reactivities of ethanol and gasoline are very similar for RPM > 900.
- Also heat-release rates are very similar (example for 1500 rpm).
- Ethanol: RON = 107, MON = 89.
- Gasoline: RON = 91 and MON = 83.
- But octane rating is different. Rpm effect.
- At very low engine speed gasoline develops LTHR.
  - HRR profiles become dissimilar.

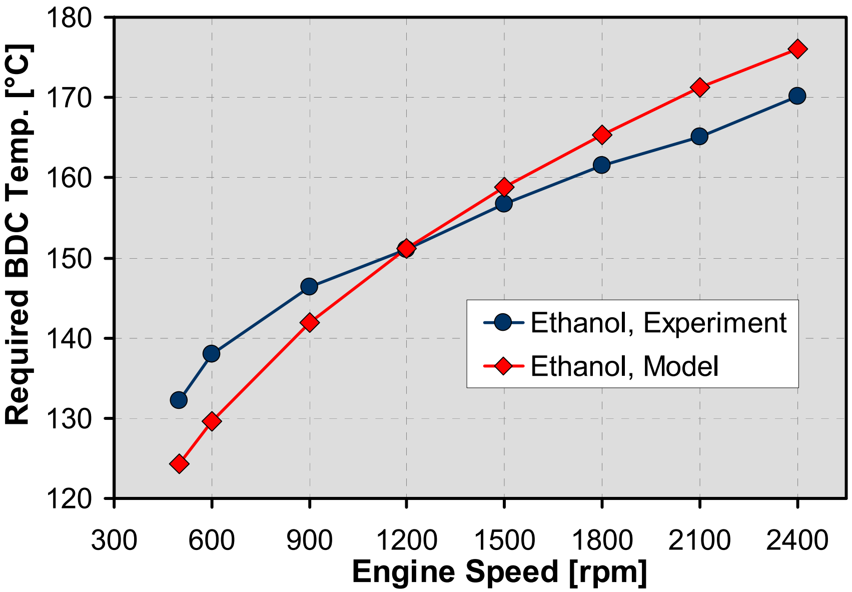






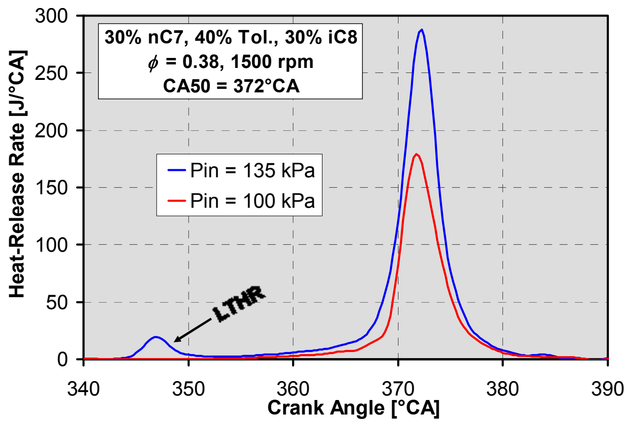
Model Evaluation for Speed-Sweep

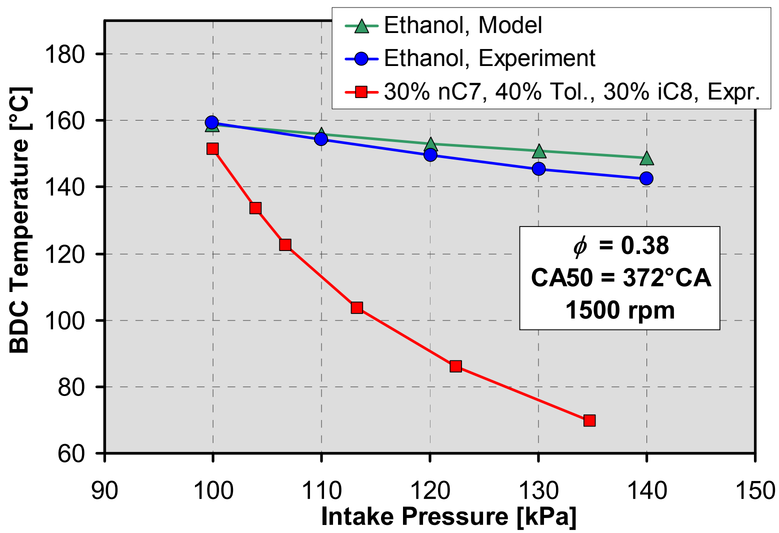
- Evaluate latest ethanol mechanism from LLNL / National University of Ireland - Galway.
- Courtesy of W. Pitz and H. Curran.
- 55 species and 350 reactions.
- For model evaluation, it is beneficial to compare the BDC temperature required to achieve the same start of combustion (SOC) as engine speed changes.
- Identical BDC temperatures at 1200 rpm.
- Slightly larger changes of T_{bdc} are required for model.
- Could be caused by too-low temperature sensitivity of the model.
  - Evaluate as a future step.
- Overall, very good agreement.
  - No tuning was performed.

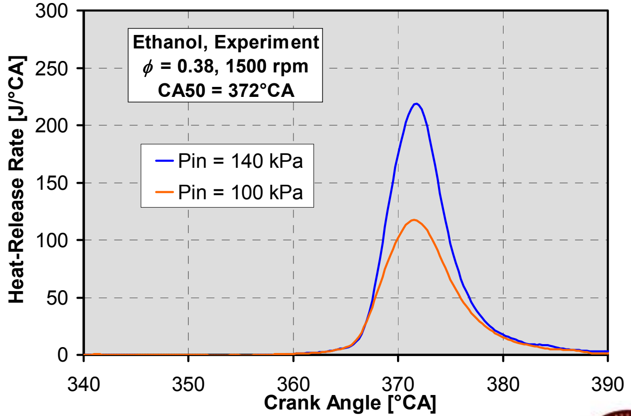


Intake Boost Sweep

- The autoignition of ethanol has very low dependence on intake boost.
- In contrast, a blend of 30% n-heptane, 40% toluene, and 30% iso-octane shows strong dependence on boost.
- Happens mostly because the increased pressure triggers onset of LTHR.
- Does not happen for ethanol, which remains a single-stage ignition fuels for boosted conditions.
  - Consistent with proven anti-knock properties for boosted SI operation.
- Ethanol model shows slightly too low boost sensitivity.
  - However, overall very good agreement.







Future Work FY 2009 – FY 2010

- Continue evaluation of ethanol and gasoline over a wide range of conditions.
  - Particularly assess influence of boost, EGR, ϕ, and fuel-vaporization cooling.
  - Evaluate the ethanol chemical-kinetics mechanism with regards to EGR, T_{in}, and ϕ.
  - Use model to investigate the influence of EGR, ϕ, and boost on the laminar flame speed.
- Finalize detailed design of DISI research engine with all-metal and optical configurations.
- Complete the fabrication of parts for all-metal configuration.
- Assembly and commission engine to allow initial performance testing.

2009

2010

- Perform experiments to assess DISI engine performance and efficiency, and the onset of knock as a function of ethanol/gasoline fuel blend and CR.
- Assess the robustness of the stratified spray-guided combustion system as the fuel composition and intake-boost pressure change.
  - Continuous monitoring for misfire cycles.
- Apply advanced optical diagnostics (including high-speed imaging) to identify the in-cylinder processes that are responsible for sporadic misfire cycles.
  - Focus on the conditions prevailing near the spark gap (fuel concentration and flow field) and the ensuing early flame growth.

Summary

- Good progress have been made to commission a new advanced future fuels research engine laboratory.
- Design is nearly complete for an optically-accessible research DISI engine with all-metal performance-testing capability.
  - Spray-guided stratified charge SI combustion system.
  - Collaborating with GM on hardware and relevant combustion-chamber geometry.

- The new DISI engine will be installed and commissioned late FY2009.
- Will allow performance testing with all-metal engine configuration over wide ranges of operating conditions (including high intake boost) and alternative fuel blends.
- Perform advanced high-speed optical diagnostics of modes of operation that show less-than-desired performance or robustness, *i.e.* unacceptable misfire frequency.

- Have performed initial assessment of autoignition characteristics of ethanol. More tests in HCCI Fundamentals lab planned for FY2009.
- The latest ethanol mechanism from LLNL / NUI Galway captures well autoignition over ranges of engine speed and intake boost.
  - After evaluation of EGR, ϕ, and T_{in} sensitivity, use model to investigate conditions relevant for new DISI engine, *i.e.* onset of knock and laminar flame speed.