Advanced Lean-Burn DI Spark Ignition Fuels Research

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Project ID: FT006

Overview

Timeline

- Project start date: 2008 Jan
- Project directions and continuation are reviewed annually.

Budget

- Project funded by DOE/VT.
- FY09 - $600 K.
- FY10 - $630 K.

Barriers

- Project provides science to support industry to develop advanced lean/dilute-burn SI engines for non-petroleum fuels.
- 45% peak efficiency.
- Inadequate understanding how to achieve high robustness for SI engines using alternative fuels:

1. DISI with spray-guided stratified-charge combustion.
2. Well-mixed charge, highly boosted and downsized.

Partners / Collaborators

- PI: Sandia (M. Sjöberg)
- 15 Industry partners in the Advanced Engine Combustion MOU.
- General Motors.
- D.L. Reuss (formerly at GM)
- HCCI Lab at Sandia (J.E. Dec).
- LLNL (W. Pitz) & NUI – Galway (H. Curran).
- UW-Madison (R. Reitz).
- UNSW – Australia (E. Hawkes).
- Reaction Design Inc.

Barriers - Relevance

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

- How emerging future fuels will impact the new, highly-efficient DISI light-duty engines currently being developed.
- How to mitigate potential barriers (*e.g.* ensure robust flame development under lean/dilute conditions, and avoid preignition/superknock).

DISI lean-burn with spray-guided stratified charge

- Plagued by occasional misfires for low-NO_x operation with EGR.
- Incomplete understanding of fuel-air mixture preparation/ignition/flame development.
- Ethanol has lower Stoichiometric AFR than gasoline (9.0 vs. 14.6).
- Requires 60% more injected fuel mass, which influences fuel stratification.
- ≈400% more vaporization cooling, which influences early flame development and combustion.

Highly boosted and downsized SI with well-mixed charge

- Onset of low-speed preignition/superknock limits full potential.

- Focus for the first years is on ethanol / gasoline blends. Consider other blends and components (*e.g.* butanol) based on industry interests and feedback.

Overall Approach

Lab and engine build-up and commissioning :

- Base the 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 on latest generation single-cylinder research cylinder head.
  - Spray-guided stratified charge SI combustion system. (Can be operated with homogeneous charge).
  - Suitable fuel injectors, and high-energy ignition system.
  - Add optical access and overpressure-protection features.

Research:

- First, conduct performance testing with all-metal engine configuration over wide ranges of operating conditions and alternative fuel blends.
  - Speed, boost, EGR, and stratification level. Develop needed statistics.
- Second, apply a combination of optical and conventional diagnostics to develop the understanding needed to improve operating conditions that show less-than-desired robustness, or are plagued by preignition/superknock.
  - Include full spectrum of phenomena; from valve motion / intake flow, to development of flame.

Supporting modeling:

- Conduct CHEMKIN chemical-kinetics modeling of flame-speed and autoignition for detailed knowledge of governing fundamentals.
  - Perform validation experiment in HCCI fundamentals lab and compare with literature.
- Collaborate with CFD modeling teams.

Technical Accomplishments

Future fuels DISI lab:

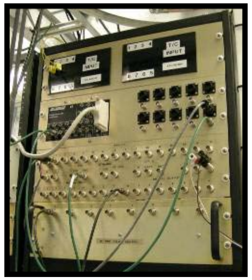
- Finished detailed design of engine, and installed a majority of engine components and subsystems.
  - Installation of final parts is currently in progress.
- Installed required high-speed data acquisition and control electronics.
  - Computer control of rpm, spark, injection etc. enables transient-testing capability.
- Installed emissions and smoke meters.
- Measured accelerations to confirm a well-balanced single-cylinder engine.
- Installed and tested high-speed imaging of valve motion and spark.
- Specified optical diagnostics techniques for high-speed PIV and PLIF.
  - In the process of placing order for high-speed lasers.
- Performed initial computational study of flame-speed fundamentals.

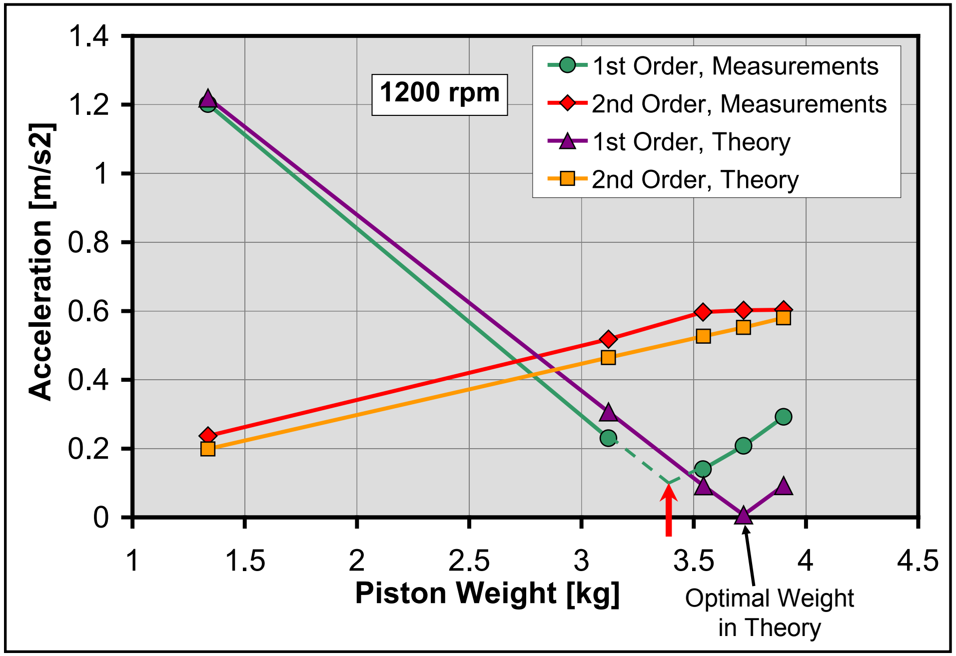
Initial fuel evaluation for DISI operation:

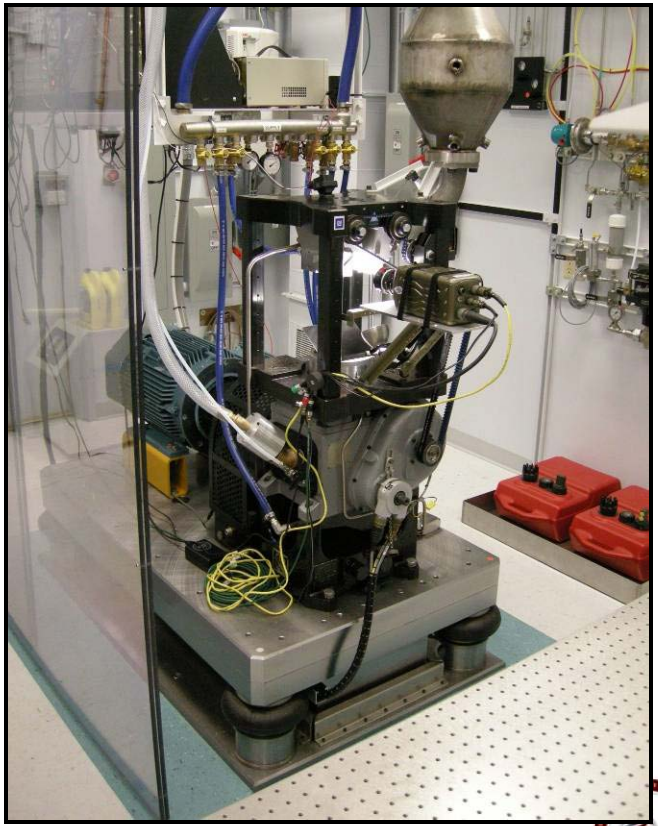
- Finished tests in the HCCI lab to assess ethanol and gasoline autoignition characteristics (as related to knock and flame speed for SI).
  - Including EGR and fuel-vaporization cooling effects.
- Finished evaluating latest ethanol chemical-kinetics mechanism from LLNL.

Engine / Lab Installation

- Engine is assembled and has been motored at 2000 rpm.
- Two-tank fueling system is being installed.
  - Allows fuel composition to be varied during A-B-A test.
- Control and measurement electronics is fully functional.
- Measured accelerations with various dummy piston weights.
  - Determined that optimal piston weight is 3.4 kg, lower than “standard” theory predicts.



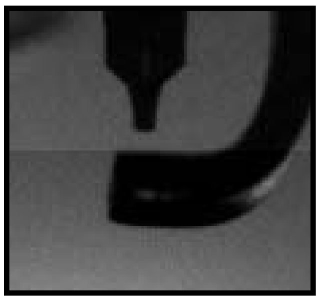




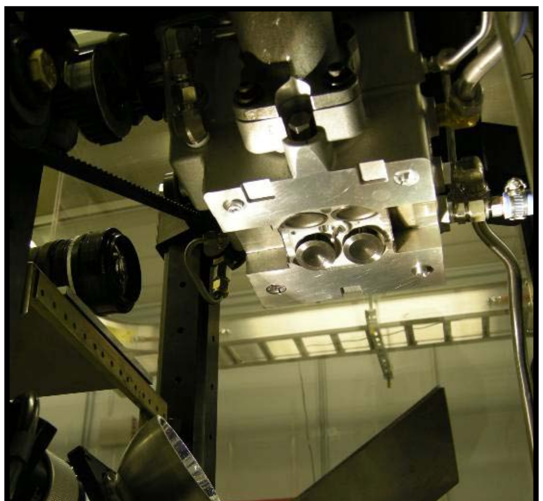
Valve Motion and Spark Imaging

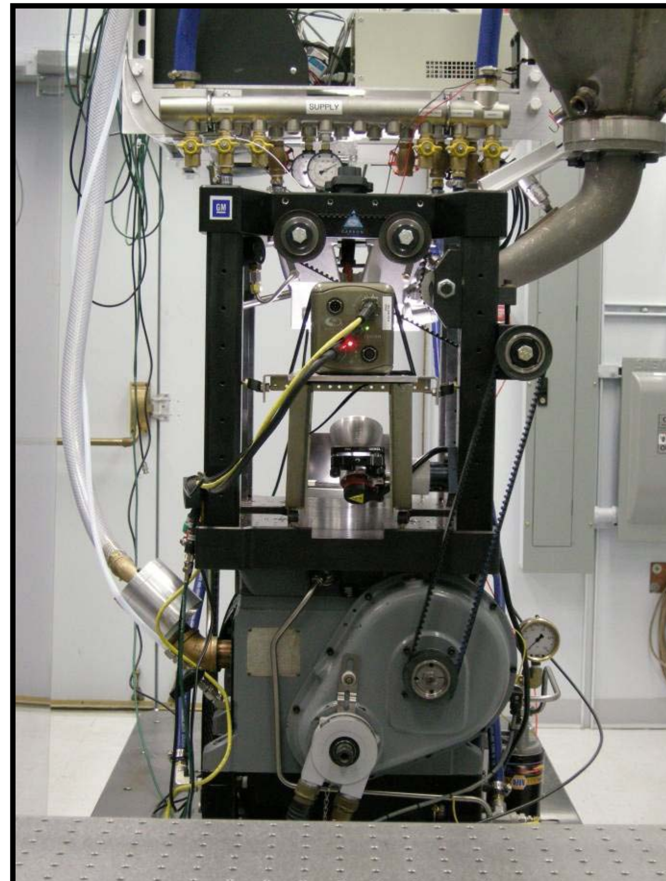
- High-speed imaging has been tested with Phantom 7.1 camera.
- Valve motion – dynamic measurement of valve lift and repeatability.
- Spark visualization – confirm repeatable ignition source – Bosch 100mJ high-energy spark.

1200 rpm, 0.1°CA
resolution = 72 kHz



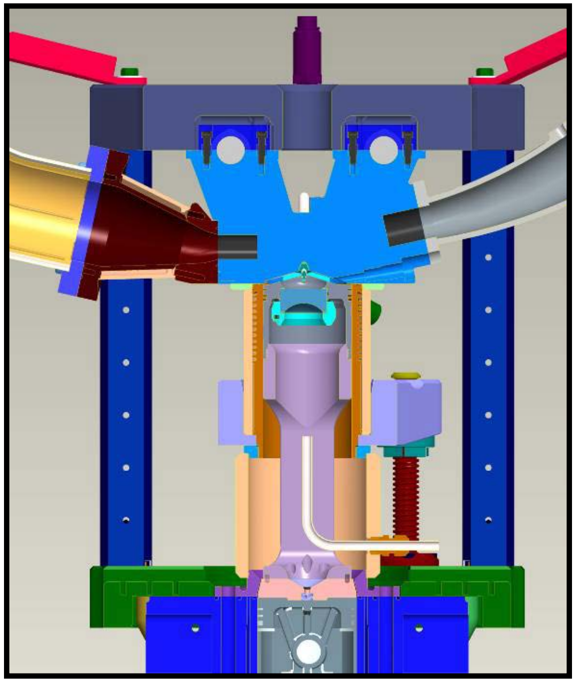
2000 rpm, 3°CA
resolution = 4 kHz

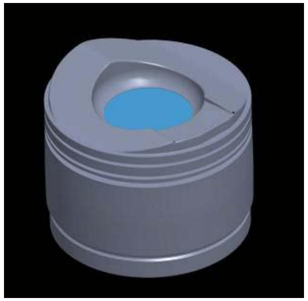


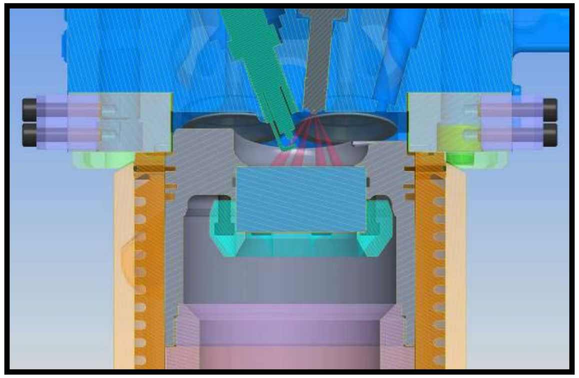


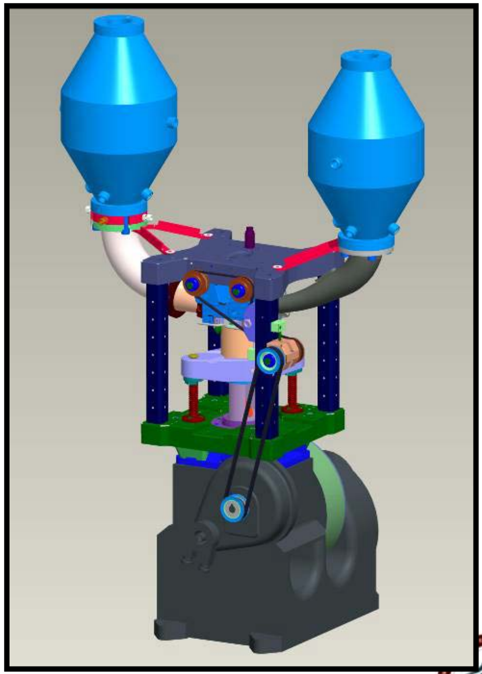
Research Engine Layout

- Two configurations of drop-down cylinder engine:
- All-metal: Metal-ring pack and oil-jet cooling of piston (incl. lower cylinder for oil control). Water-cooled exhaust for continuous operation.
- Optical: Pent-roof windows, piston bowl window, 45° mirror, and quartz cylinder.
- Identical combustion chamber geometry for both configurations. 0.55 liter swept, CR = 12.
- Hollowed-out Invar screws of window retainer for overpressure protection and temperature-independent preclamping force.
- GT-Power was used for sizing exhaust runner / tanks for minimal pressure oscillations.



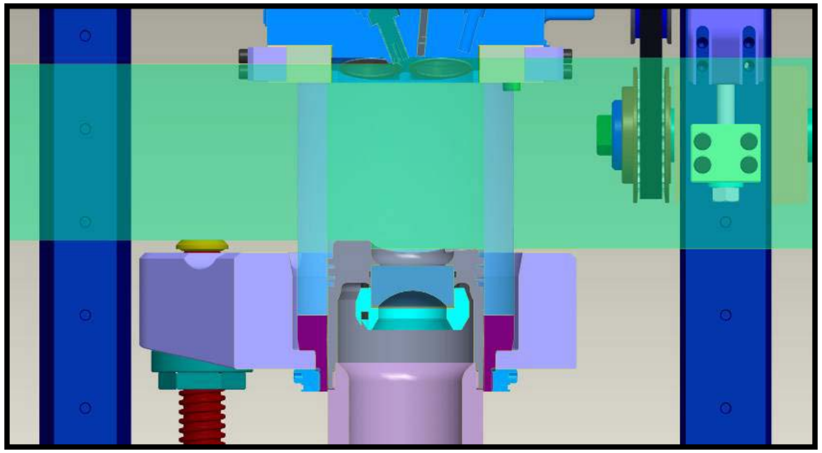


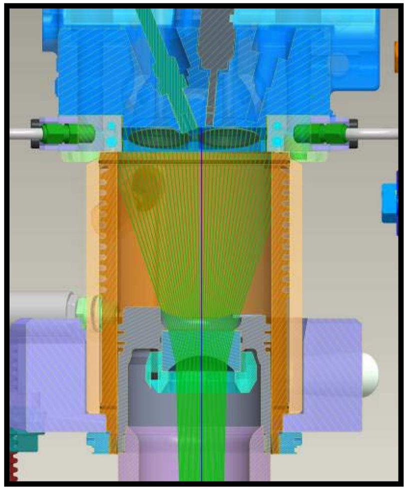


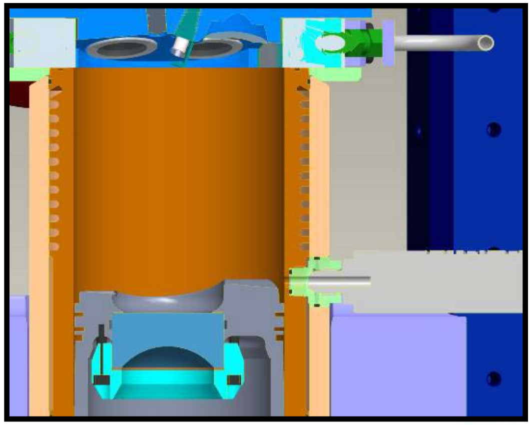


Diagnostics Development

- Stratified charge DISI engines have good potential for high efficiency.
- Occasional misfire/partial burn cycles are a barrier to optimal implementation.
- Plan to probe cycle variability at every stage and compare with IMEP.
  - Intake valve motion – direct imaging.
  - Intake flow and pressure – high-speed PIV, pressure transducers, and hot-wire anemometry.
  - Compression flow structure – high-speed PIV.
  - Spark event – direct imaging, voltage and current measurement for energy.
  - Fuel concentration and flow near ignition location - high-speed PLIF and PIV.
  - Flame development – direct imaging and seeder particle disappearance.
- Clarifying preignition/superknock requires a similar systematic approach.
- In the process of purchasing high-speed lasers for PIV and PLIF.







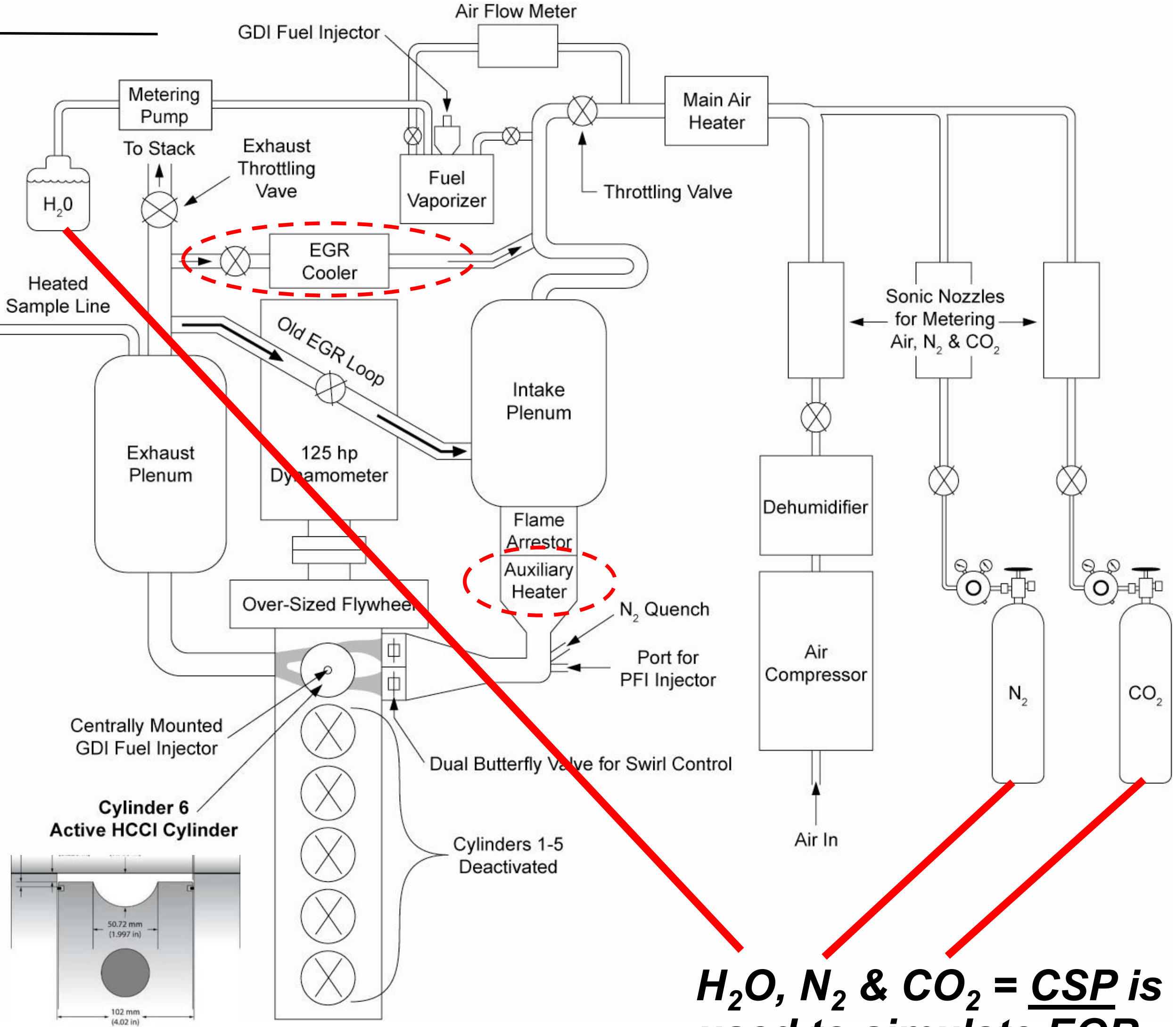
Fuel Evaluation for DISI Research

- Engine knock must be avoided when operating with alternative fuels $\Rightarrow$ examine the autoignition characteristics of these fuels.
- Performed experiments in the HCCI lab to assess ethanol autoignition characteristics and compared with gasoline, iso-octane and other fuels.
- Covered wide range of conditions:
  - Engine speed.
  - Intake boost pressure.
  - Fuel/air equivalence ratio – ϕ.
  - Charge temperature.
  - **EGR and constituents.**
  - Vaporization cooling.

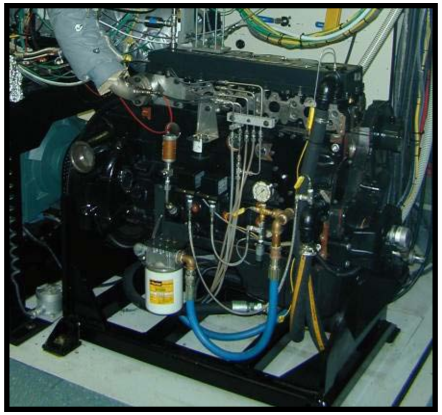
  (Engine speed, intake boost pressure, fuel/air equivalence ratio and charge temperature: **SAE Paper 2010-01-0338**; EGR and constituents: **Combustion Symposium 2010**)
- Evaluate the fidelity of existing chemical-kinetics mechanisms.
  - Being used for modeling of both knock onset and flame speed.
- Current ethanol mechanism is a joint effort between NUI – Galway (Curran, Serinyel, and Metcalfe) and LLNL (Pitz and Mehl).
  - Detailed with 58 species and 310 reactions.

All-metal HCCI Engine

Premixed fueling is used for all data presented.



Cummins B
0.98 liter / cyl.

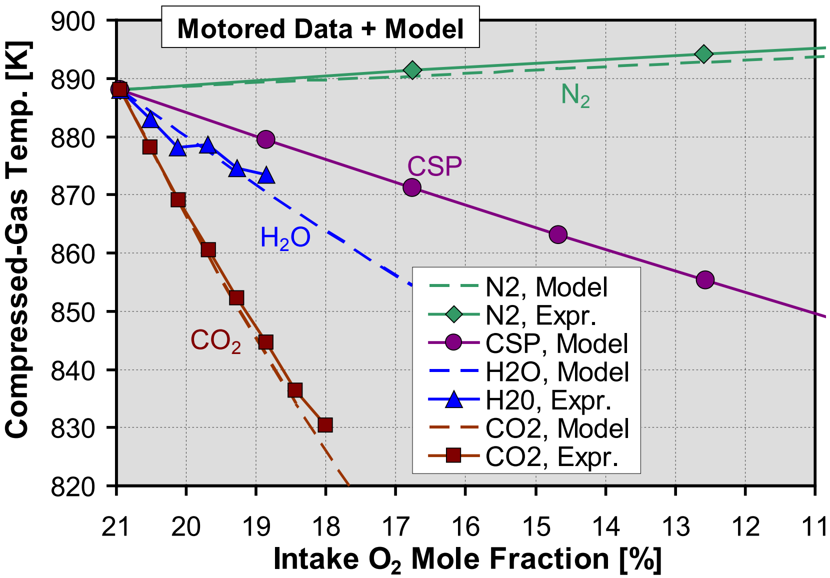


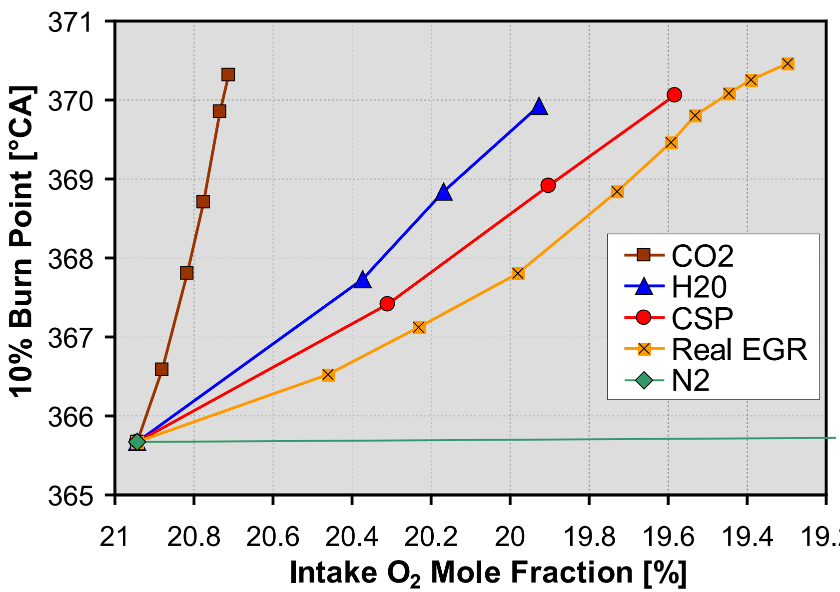
CR = 14

H_2O, N_2 & CO_2 = <u>CSP</u> is used to simulate EGR.

Ethanol Retard for CSP and Components

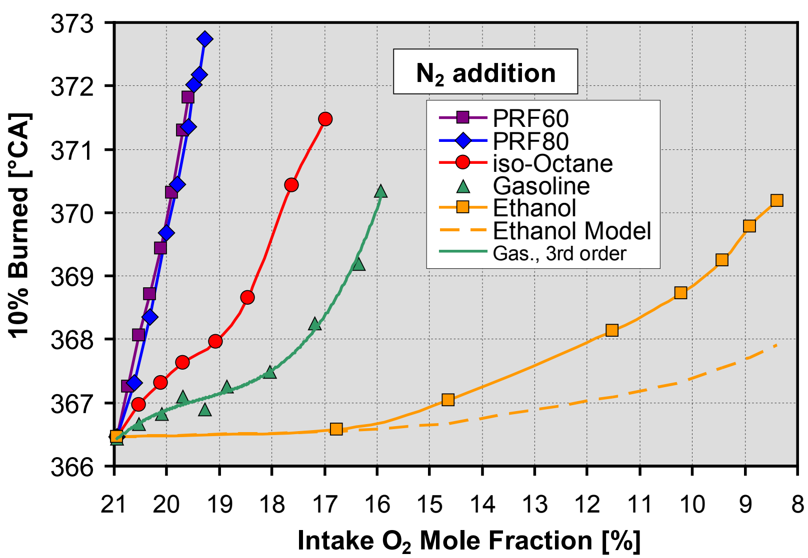
- Establish baseline point. CA10 = 365.6°CA for T_{in} = 145°C. Then add EGR.
- The retarding effects are ordered consistently with the "cooling capacity" of the added gases - **thermodynamic effect**.
- However, H_2O line falls closer to CSP than expected, because of a weak enhancing **chemical** [H_2O] effect.
- Real EGR has a weaker retarding effect than CSP, also indicating a weak enhancing **chemical** effect of trace species.
- N_2 addition gives most reduction in [O_2] for least change in heat-capacity.

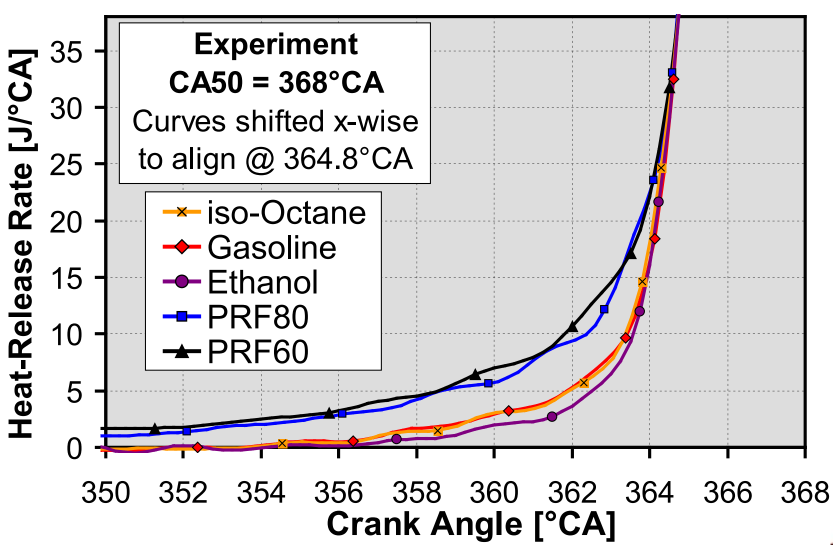




Comparing $[O_2]$ Sensitivities and ITHR

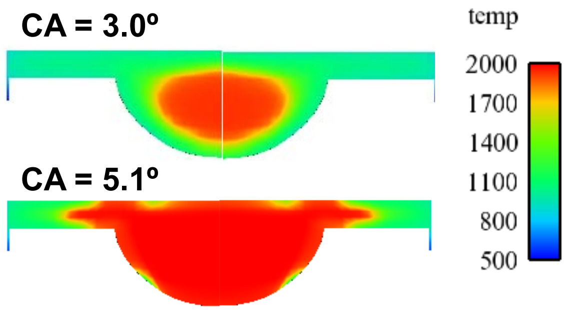
- Ethanol is very insensitive to the chemical effect of $[O_2]$ reduction.
  - Confirmed by model.
- Iso-octane is significantly more sensitive to $[O_2]$.
- Can be explained by differences in intermediate-temperature HR (ITHR).
- Ethanol breaks down late, and is a distinct single-stage ignition fuel.
- The two-stage ignition fuels PRF80 and PRF60 are much more sensitive.
  - Lower $[O_2]$ reduces both low-temperature HR (LTHR) and ITHR.

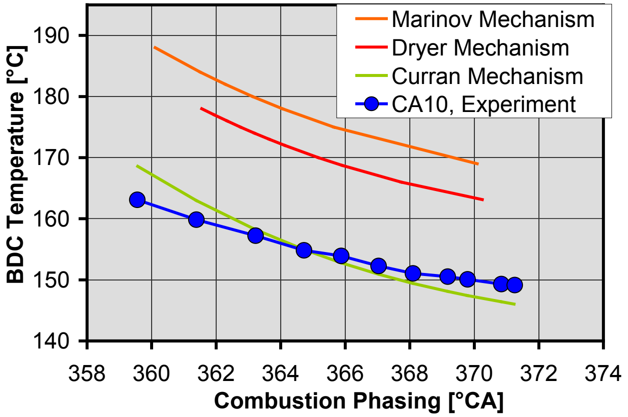




Collaborations

- HCCI Lab at Sandia (J.E. Dec).
  - Reference HCCI autoignition data for various fuels.
- LLNL (W. Pitz) & Univ. of Galway (H. Curran).
  - Chemical-kinetics mechanisms.
- UW-M (R. Reitz, J. Brakora).
  - CFD, mechanism validation and reduction.
- UNSW – Australia (E. Hawkes).
  - CFD, and mechanism validation.
- Reaction Design Inc.
  - Tools for flame-speed and flame-extinction calculations.

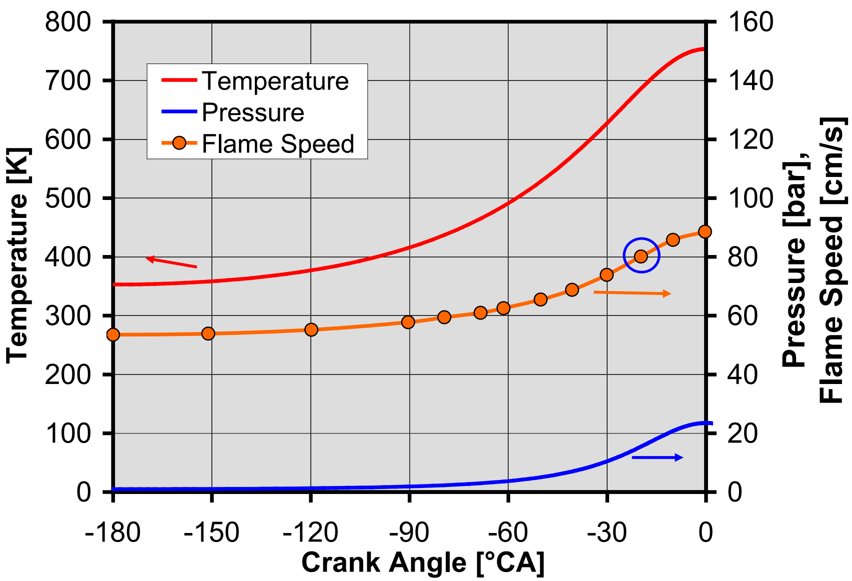




- 15 Industry partners in the Advanced Engine Combustion MOU.
- General Motors.
  - Hardware, discussion partner for combustion-chamber geometry and diagnostics.
- D.L. Reuss (formerly at GM)
  - Optical-diagnostics development.

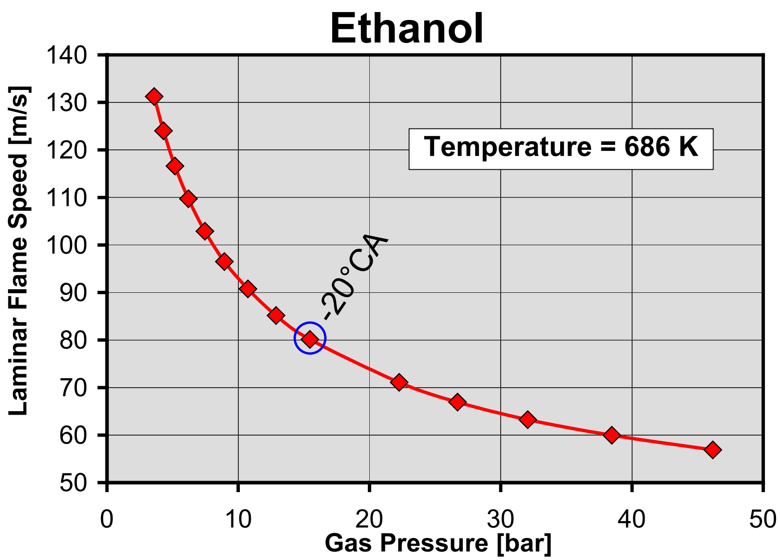
Flame-Speed Modeling

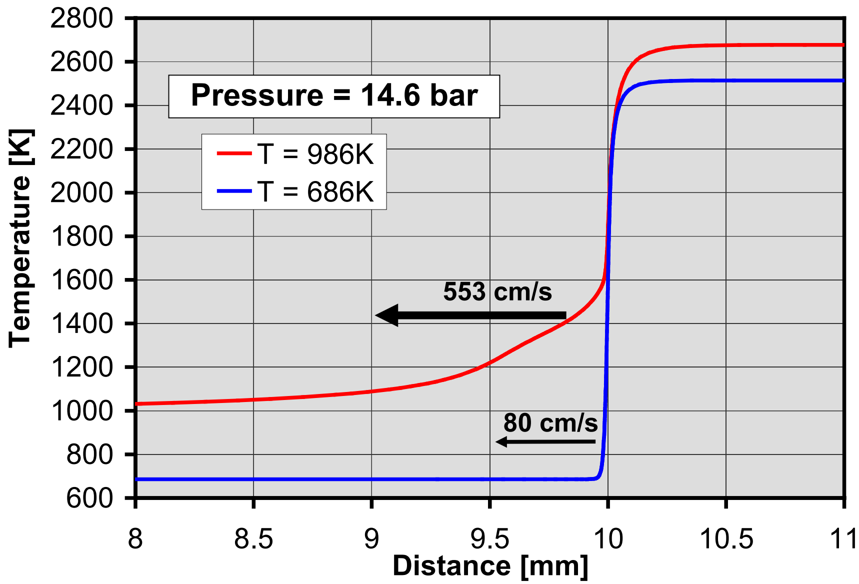
- The laminar flame speed (S_L) is one of the major parameters that determine successful flame development and combustion.
- Everything else being equal: Higher S_L is expected to lead to a more robust flame development, but also higher risk of preignition/superknock.
- Important to form a solid base for interpretation of engine results.
- Flame modeling using CHEMKIN-PRO at engine-relevant conditions.
- Examples of insights gained for ethanol, with $\phi = 1.0$.
- Flame speed increases during compression stroke.
- Competition between temperature and pressure.
- Examine variations at -20°CA.

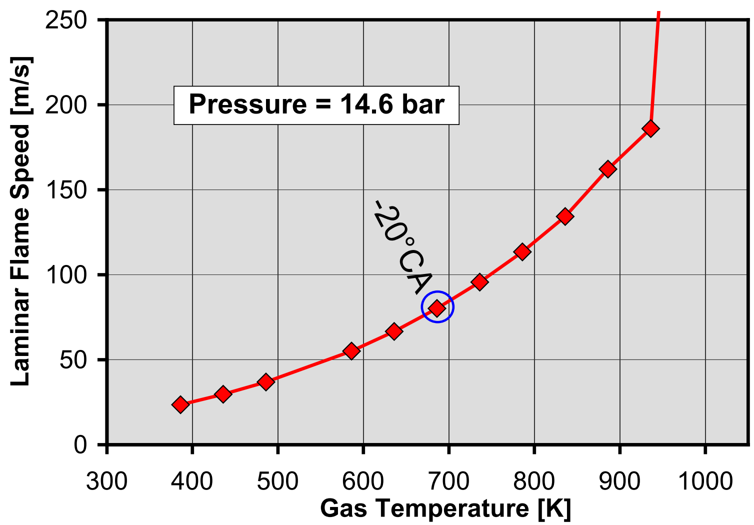


Temp and Pressure vs. S_L

- S_L decreases with pressure.
- S_L increases with temperature.
- At high temperatures, the flame speeds up and thickens because of autoignition.
- Combustion in endgas and avoidance of knock!
- HCCI data highly relevant for validation.

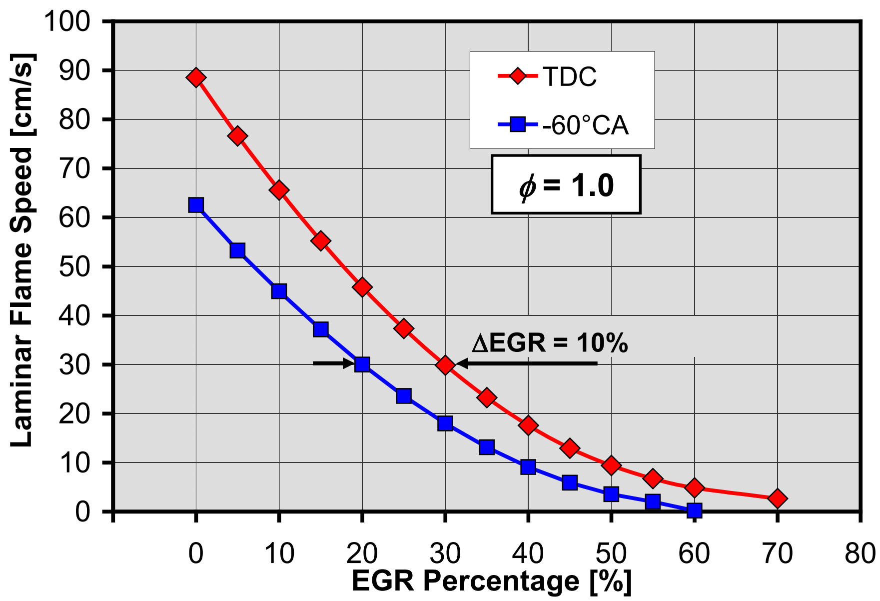


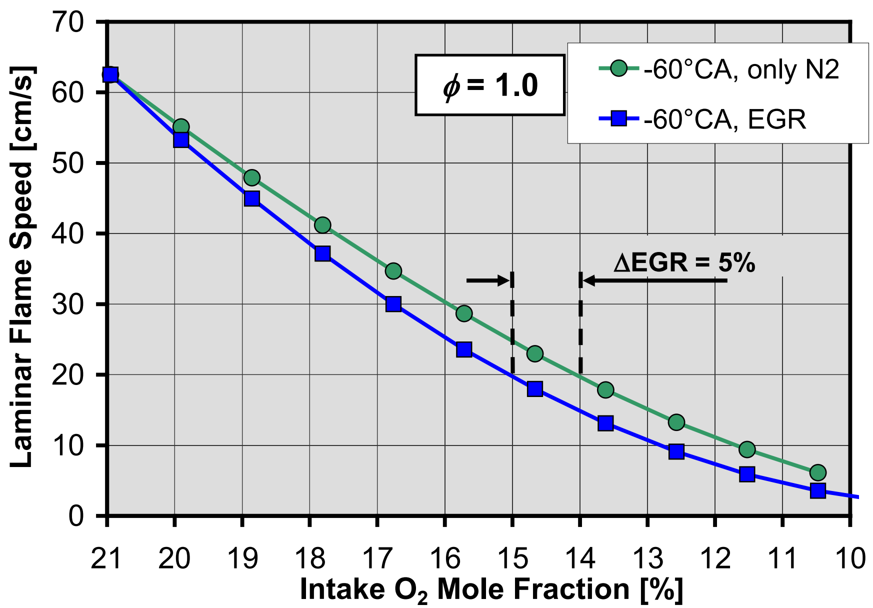




EGR Influence on S_L

- EGR is used to mitigate NO_x for lean-burn SI engines, and for knock suppression at high load. Also reduces preignition/superknock risk.
- EGR also decreases S_L, so can jeopardize combustion robustness.
- Model predicts that TDC spark would tolerate 10% more EGR for same S_L.
- However, longer burn duration with EGR, so need to spark earlier.
  - One fundamental piece to consider for high EGR operation. Use multi-spark?
- When using N_2 in lab to simulate EGR, consider that N_2 is “5%” less effective.
  - Consistent with low $[O_2]$ sensitivity from HCCI measurements.





Future Work FY 2010 – FY 2011

2010

- Commission engine to allow performance testing.
- Perform experiments to assess DISI engine performance and efficiency, and the onset of knock as a function of ethanol/gasoline fuel blend.
- Assess the robustness of the stratified spray-guided combustion system as the fuel composition and intake-boost pressure change.
  - Continuous monitoring for misfire cycles with addition of EGR to mitigate NO_x.

2011

- Apply advanced optical diagnostics to identify the in-cylinder processes that are responsible for sporadic misfire cycles.
  - Correlate variations in the early flame growth and IMEP with variations of fuel concentration and flow field near spark, large-scale intake and compression flow field, and spark energy.
- Use CHEMKIN to investigate the influence of in-cylinder conditions on the laminar flame speed and flame extinction for various fuel blends.
- Perform initial studies of preignition/superknock and discuss with industry partners.

Summary

- The new lab is ready for use and fired engine tests will commence very soon.
- Will provide <u>science-base for the impact of alternative fuel blends on advanced SI engine combustion.</u>
  - Spray-guided stratified-charge DISI.
  - Homogeneous charge SI combustion with high intake boost.
- Initial focus is on ethanol/gasoline blends.
  - Other fuels (*e.g.* butanol) will be studied depending on industry interest.
- <u>Particular emphasis will be on combustion robustness.</u>
  - Monitor misfire cycles in stratified-charge DISI mode.
  - Preignition/superknock for well-mixed boosted operation.
- First: Performance testing with all-metal engine configuration over wide ranges of operating conditions
- Then: Perform advanced high-speed optical diagnostics (PLIF, PIV) of modes of operation that show less-than-desired robustness.
- Completed assessment of ethanol autoignition over wide ranges of operating conditions in HCCI lab $\Rightarrow$ Two publications.
- Modeling of flame speed is contributing to solid science-base.