Advanced Lean-Burn DI Spark Ignition Fuels Research

Magnus Sjöberg

Sandia National Laboratories

May 10th, 2011

Project ID: FT006

Overview

Timeline

- Project provides science to support industry to develop advanced lean/dilute-burn SI engines for non-petroleum fuels.
- Project directions and continuation are reviewed annually.

Barriers

- Goal is 45% peak efficiency.
- Lack of fundamental knowledge of advanced engine combustion regimes.
- How to achieve both high combustion robustness and fuel efficiency for SI engines using alternative fuels:
  1. Lean, unthrottled DISI with spray-guided combustion.
  2. Well-mixed charge and high boost.

Budget

- Project funded by DOE/VT.
- FY10 - $630 K.
- FY11 - $650 K.

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.
- LLNL & NUI Galway, Mechanisms.
- UW Madison - KIVA modeling.
- UNSW Australia – Multi-zone Modeling.
- Sandia – Biomass Conversion Team.

Objectives - Relevance

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

- How emerging future fuels will impact the combustion systems of new highly-efficient DISI light-duty engines currently being developed.
- How the fuels and combustion systems can be tailored to each other to maximize thermal efficiency.

- Initial focus is on E85 and gasoline. Expand to other fuel blends (*e.g.* E20) and components (*e.g.* butanol and iso-pentanol) based on industry interest.

  DISI with spray-guided stratified charge combustion system
  - Plagued by occasional misfires.
  - Depend highly on fuel-air mixture preparation/ignition/flame development.
  - These processes are strongly affected by fuel properties and required fuel mass.

- Study performance for both well-mixed stoichiometric and lean operation, and for lean stratified operation, and examine the effects of fuel properties.
- Develop high-speed optical diagnostics to be used to understand how to mitigate potential barriers (*e.g.* ensure robust combustion, and avoid superknock).
- Perform HCCI experiments to exploit the unique characteristics of ethanol.

Approach

- Combine metal- and optical-engine experiments and modeling to develop a broad understanding of the impact of fuel properties on DISI combustion processes.

- First, conduct performance testing with all-metal engine configuration over wide ranges of operating conditions and alternative fuel blends.
  - Speed, load, intake pressure, EGR, and stratification level. Quantify engine operation and develop combustion statistics.
- Second, apply a combination of optical and conventional diagnostics to develop the understanding needed to mitigate barriers to high efficiency and robustness.
  - Include full spectrum of phenomena; from intake flow to development of flame, and endgas autoignition (knock).

Supporting modeling:

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

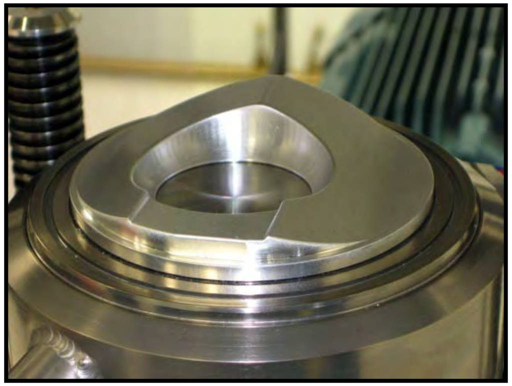
Technical Accomplishments

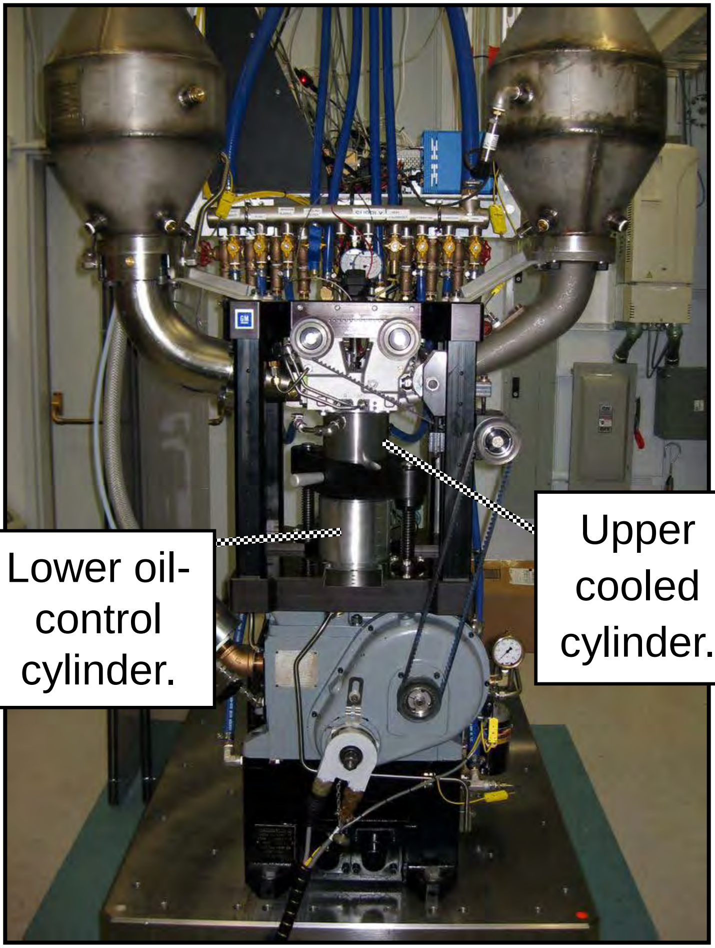
- Commissioned engine and initialized all-metal performance testing.
- Selected valve timings to provide low residuals and somewhat late IVC (mild Miller cycle).
- Performed an initial comparative study of E85 and gasoline for both well-mixed stoichiometric and lean operation, and for lean stratified operation.
- Characterized the robustness of the lean stratified spray-guided combustion system for gasoline and E85.
- Examined the direct effect of vaporization cooling on the thermal efficiency for E85.
- Optical engine experiments:
  - Installed high-speed fuel-PLIF laser and set up laser-sheet forming optics.
  - Installed high-speed PIV laser and confirmed its performance.
- Used CHEMKIN to investigate the influence of in-cylinder conditions on the laminar flame speed for strong and weak cycles.
- Demonstrated the use of partial fuel stratification with ethanol to smooth HCCI HRR by vaporization-cooling-induced thermal stratification.
  (In HCCI lab at Sandia.)

Engine Configuration

- Piston bowl design is based on recommendations from GM.
  - Modified with cut-out for viewing into bowl.
  - Production-engine metal-piston rings.

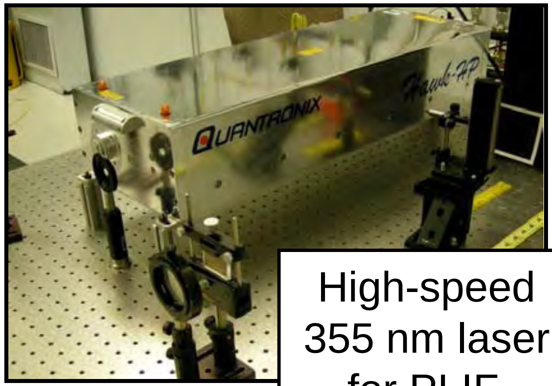
Oil and air jets.





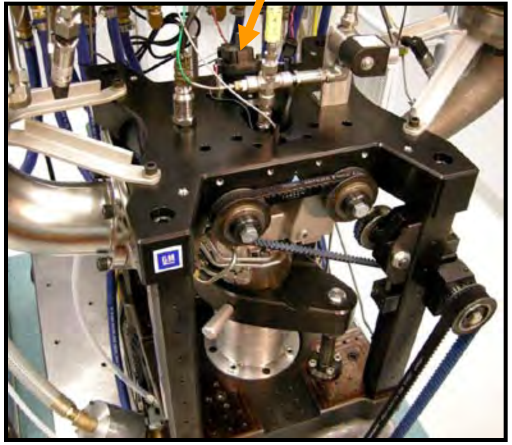
Lower oil-control cylinder.

Upper cooled cylinder.



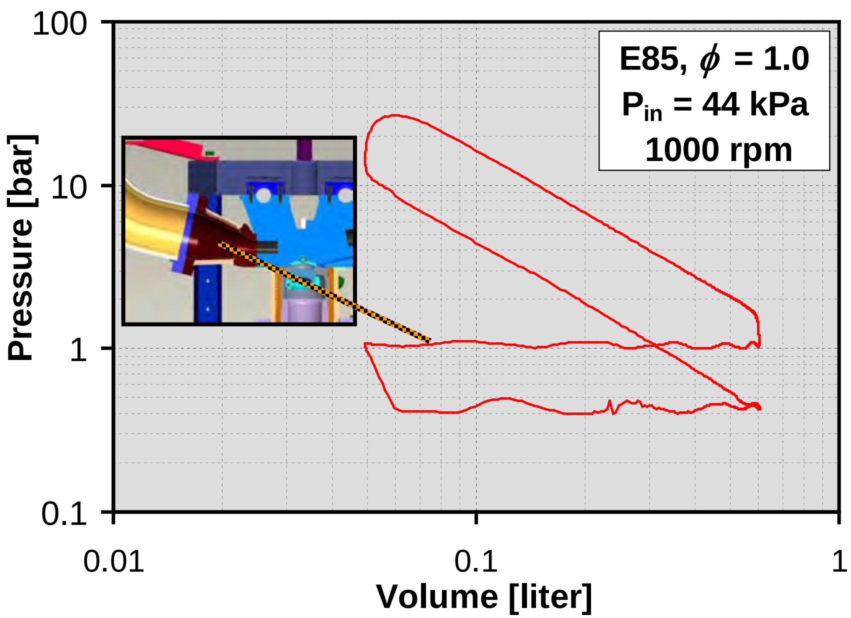
High-speed 355 nm laser for PLIF.

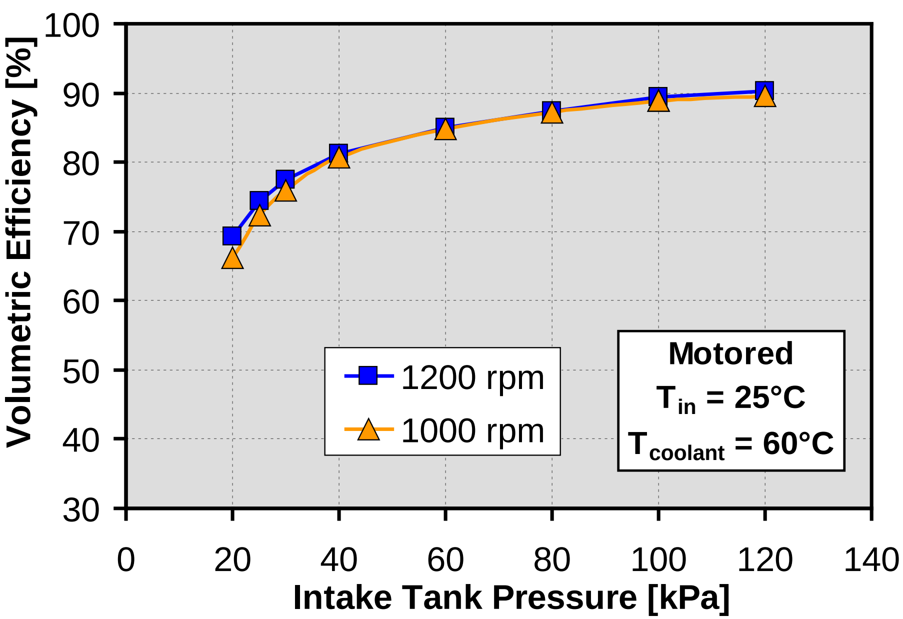
High-energy spark coil.



Engine Breathing

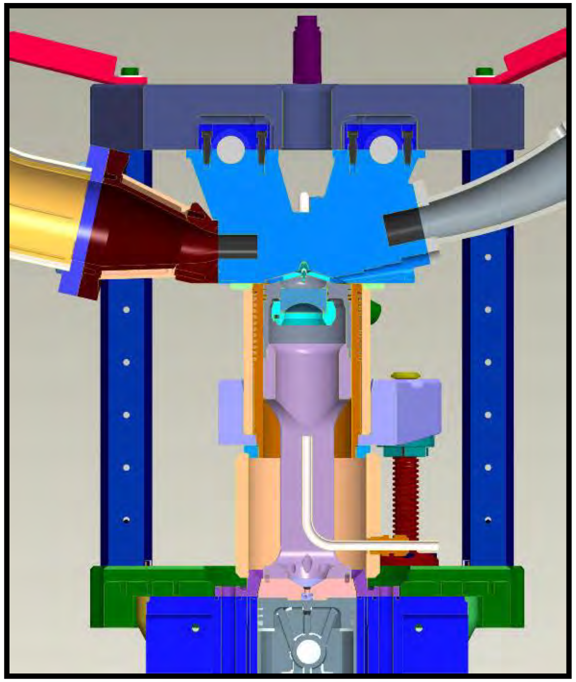
- Bore = 86.0 mm, Stroke = 95.1 mm, 0.55 liter swept volume, CR = 12.
- Selected valve timings to avoid valve overlap (not needed for low engine speeds.)
- Provide <u>low residual level</u> (A) and somewhat late IVC (very mild Miller cycle).
- Volumetric efficiency remains high even for low P_{in}.
- Expanding exhaust-port/runner design provides <u>low-amplitude pressure oscillation</u> during exhaust stroke (B), as predicted by GT-Power.
- A and B minimize cyclic variability of residual mass.
  - Residuals are now a relatively small factor when evaluating cyclic variations.

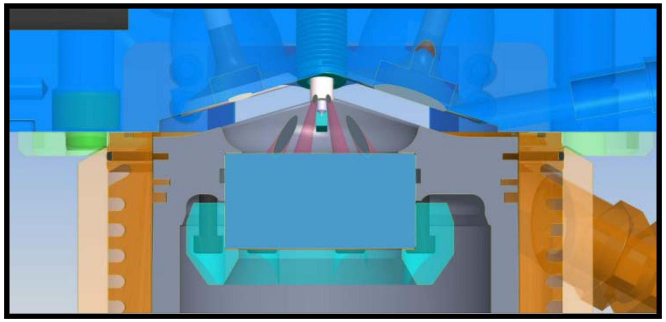


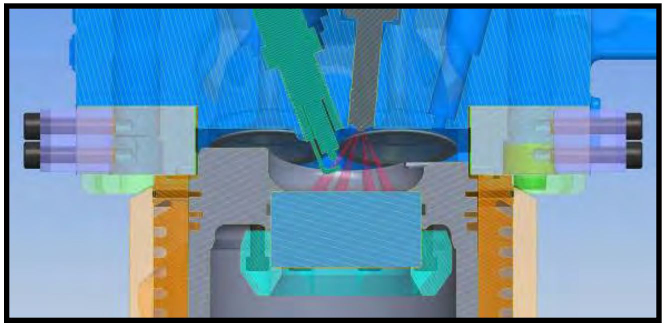


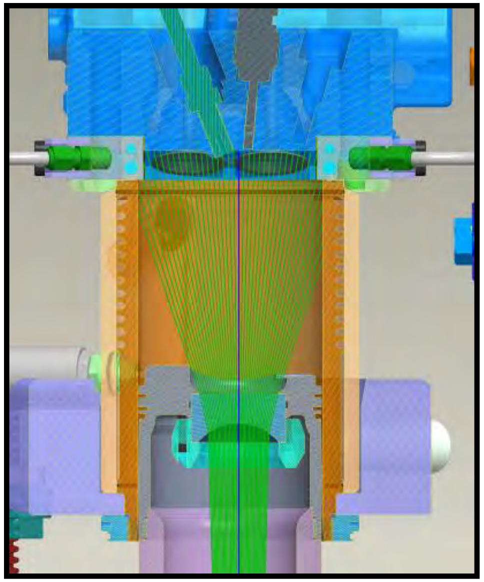
Research Engine Layout

- Two configurations of drop-down single-cylinder engine.
- <u>All-metal:</u> Metal-ring pack and air/oil-jet cooling of piston (with lower cylinder for oil control). Water-cooled exhaust for continuous operation.
- <u>Optical:</u> Pent-roof windows, piston bowl window, 45° mirror, and quartz cylinder.
- Identical combustion chamber geometry for both configurations, so no discrepancy between performance testing and optical tests.
- 8-hole injector with 60° included angle ⇒ 22° between each pair of spray center lines. Spark gap is in between two sprays.









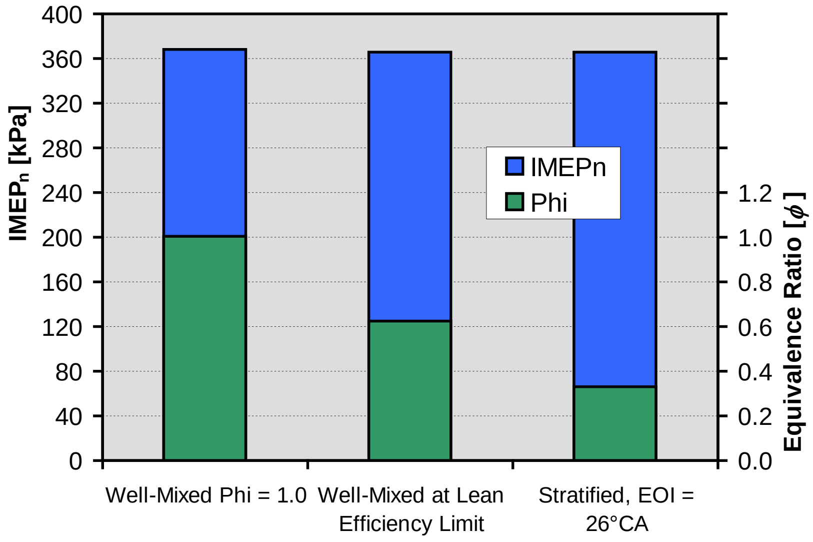
Parameter Space

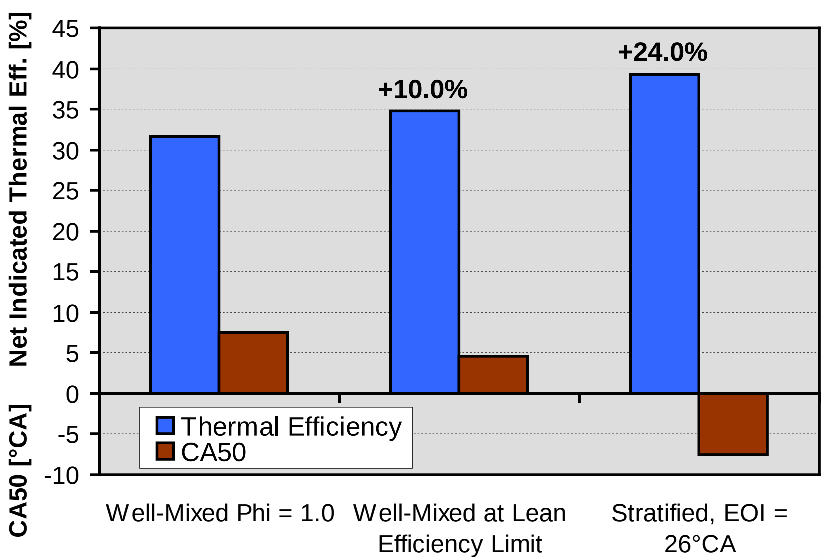
- The parameter space is huge for performance testing.
  - Grouped as hardware, static parameters & operating variables.
- Performed initial comparative study of E85 and gasoline.
  - BMEP = 3 bar, so need to maintain $IMEP_n$ ≈ 370 kPa (all 4 strokes) for all comb. modes.
- Allows assessing the basic characteristics of combustion at one low load condition.
  - One piece of the big picture.
  - Low load is relevant for stratified operation.
  - Study thermal efficiency and cyclic variability.
- Acquired data for 500 cycles per steady-state operating point.
  - Cylinder, intake, exhaust, & fuel pressure.
  - Exhaust emissions and smoke.
- All presented well-mixed cases have spark timings for max $IMEP_n$ (≈ MBT-timing).

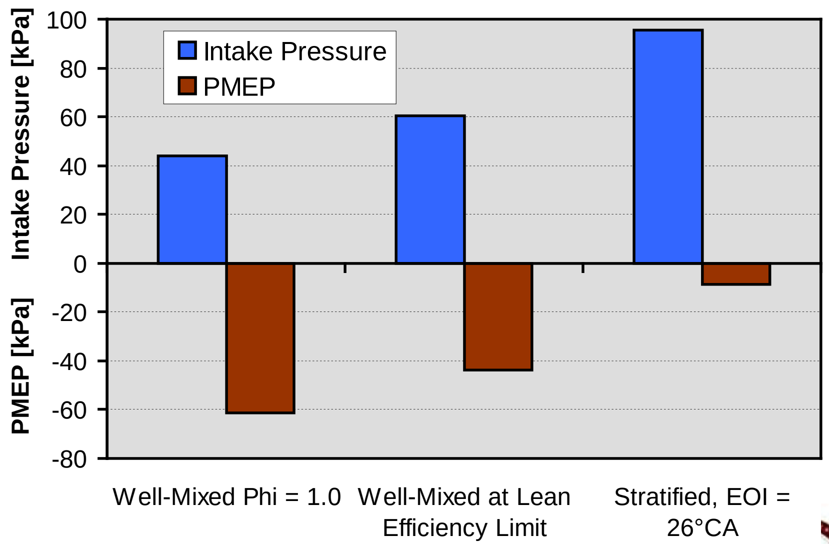
Parameter	Current Study
CR	12
Piston Bowl	∅ 46 mm
Intake Flow	Tumble
Valve Timings	For Minimal Residual Level
Injector & Spray Targeting	Bosch 8 x 60°C Straddling Spark
P_{inj}	170 bar
$T_{coolant}$	60°C
T_{in}	26°C
Engine Speed	1000 rpm
$IMEP_n$	370 kPa
$P_{exhaust}$	100 kPa
Intake Pressure	44 – 95 kPa
End of Injection	-294 to -25°CA
Spark Timing	-36 to -14°CA
Spark Energy	6 – 116 mJ
EGR / $[O_2]_{in}$	21 – 17% O_2
Fuel Type	E85, Gasoline

Gasoline Results

- Thermal efficiency (TE) improves with lean and lean-stratified operation.
- Decreased pumping work is important factor.
- Higher thermodynamic cycle efficiency for compression/expansion is largest factor.
  - Lower in-cylinder heat transfer and less exhaust heat (due to higher γ).
- TE for stratified would ⇑ with later CA50, but spark timing is not independent of EOI. (Examine in two slides.)

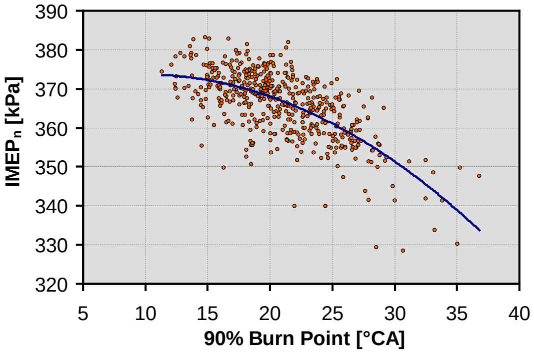




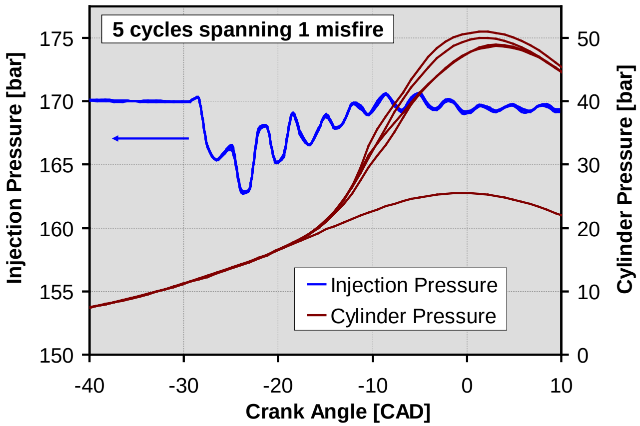


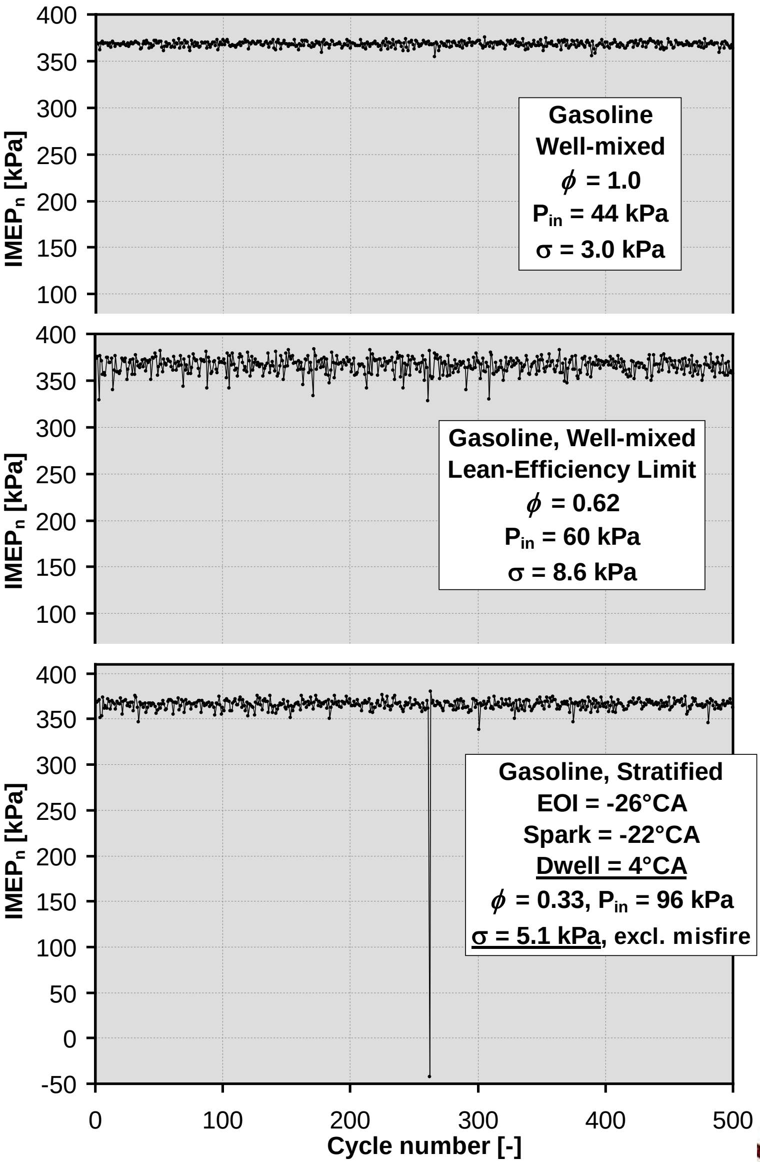
Gasoline Cyclic Variability

- Stoichiometric operation is very stable.
  - Partly thanks to low residual level ~5.7% by mass at this condition.
- Increased variability at lean efficiency limit.
  - Long burn duration, with outlier cycles.



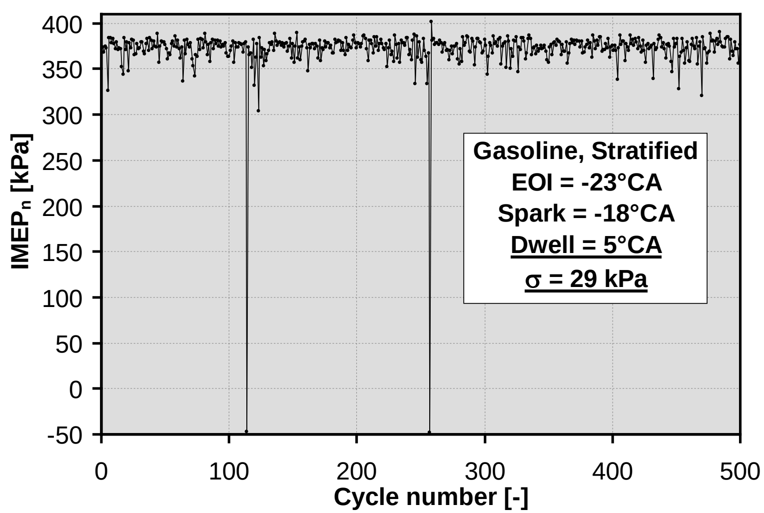
- Stratified combustion is fairly stable.
  - But 1 of 500 cycles misfires.
  - Not caused by injector malfunction.
  - Need optical diagnostics to find cause.

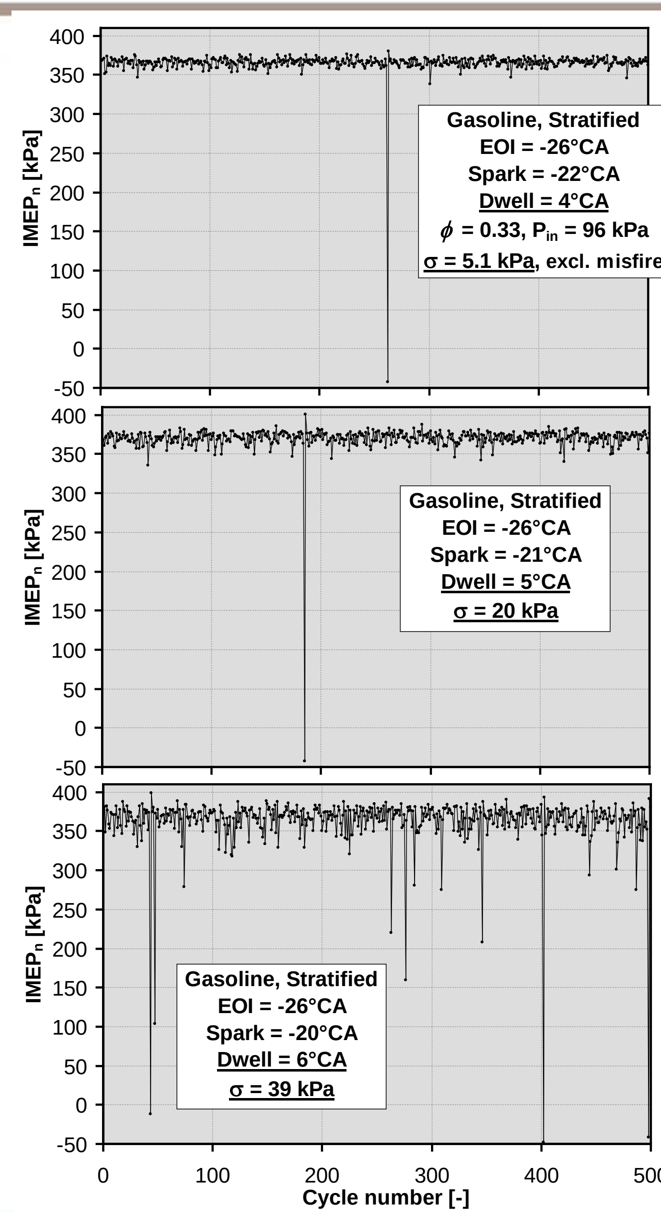




Stratified Spark-Timing Window

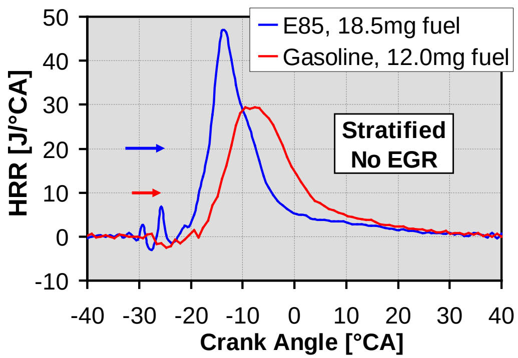
- Stable stratified combustion requires careful match of the spark timing to the injection event.
- Retarding the spark to phase CA50 closer to TDC does not work.
- Moving EOI and Spark in tandem improves TE, but higher cyclic variability and more misfires.
- Instead EGR can be used to phase CA50 later.
  - Study with E85.

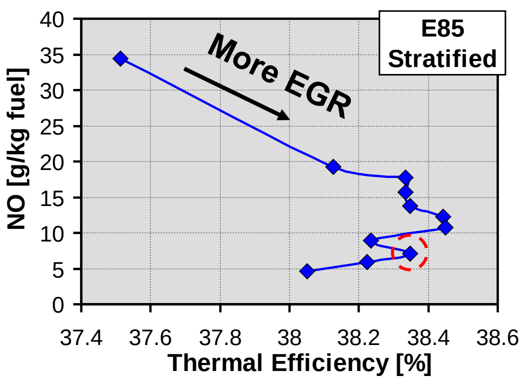


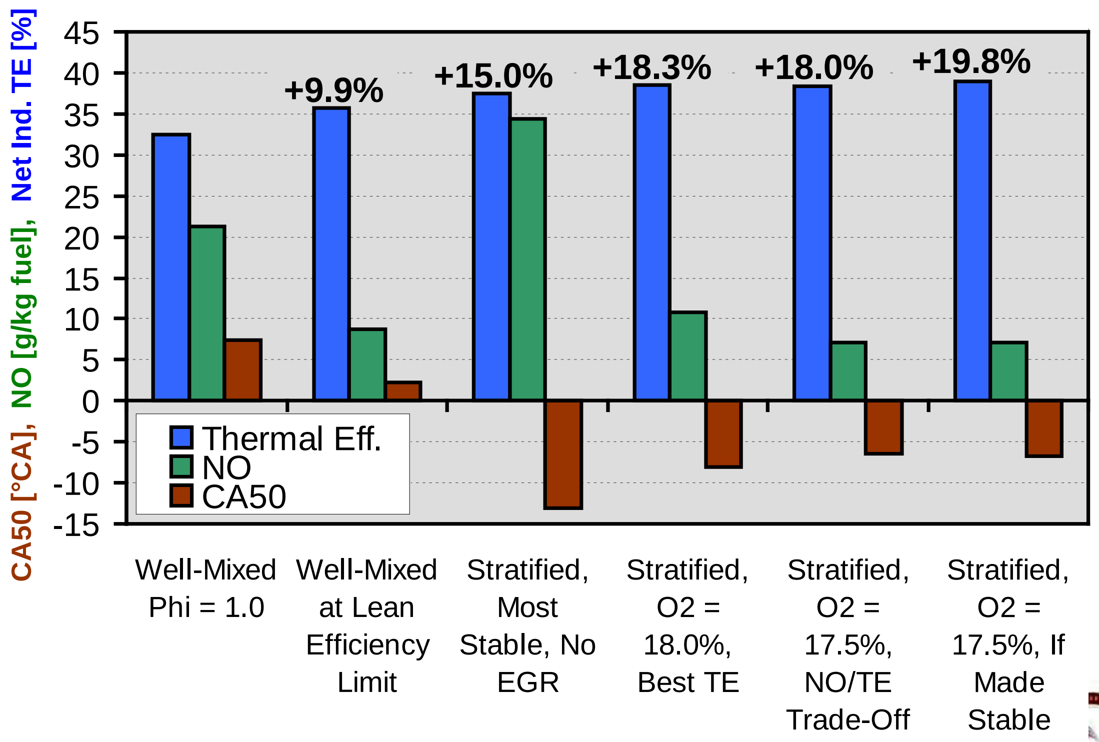


E85 Results

- TE improvement with well-mixed lean is nearly identical to gasoline.
- Without EGR, TE improvement with stratified oper. is only +15%, vs. +24% for gasoline.
- CA50 is very early, partly due to faster combustion.
  - Fuel jets have 55% higher kinetic energy, and HRR is strongly influenced by mixing rates.
- Apply EGR (N_2 dilution) to phase CA50 later. Reduces NO as well. Find best trade-off.
- Lower cyclic variability would improve thermal efficiency. (Examine in next slide).
- TE improvement is still less than for gasoline. (Examine in three slides).

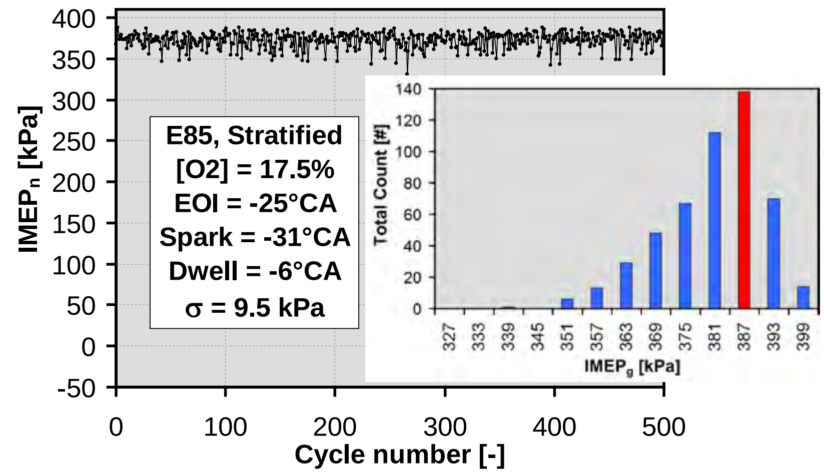


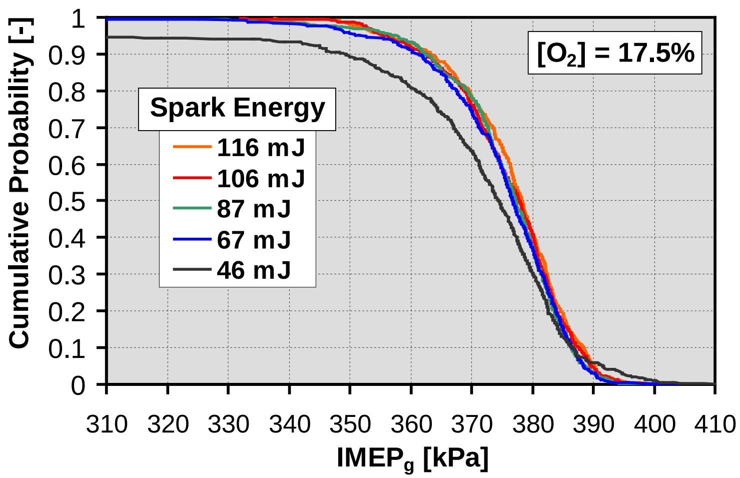


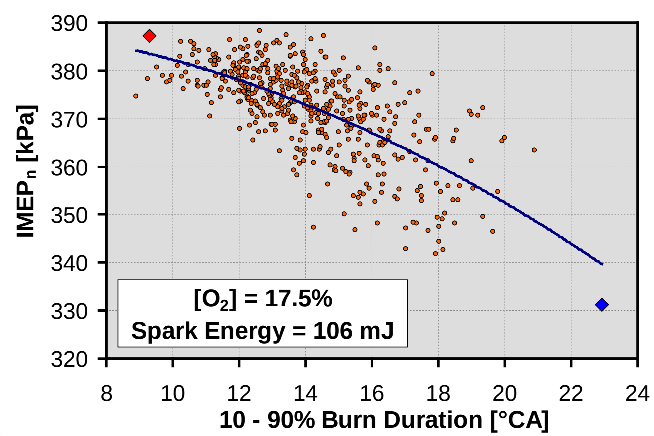


Stratified E85 Cyclic Variability

- Cyclic variability increases with more EGR.
- Higher TE would be realized if all cycles produce high IMEP.
  - Need to understand cyclic variability before suggesting ways to achieve this.
- Spark-energy sweep shows that <u>the problem is not caused by failure to ignite</u>, as long as high spark energy is used.
- For high spark energy, most low-IMEP cycles have long burn durations.
- Suggests that low IMEP is produced by slow and incomplete flame propagation.
- Examine if S_L is relevant for explaining two extreme cycles.

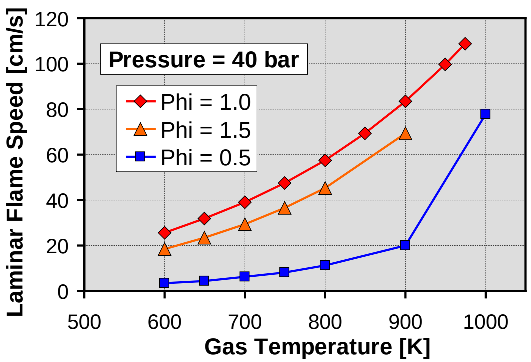




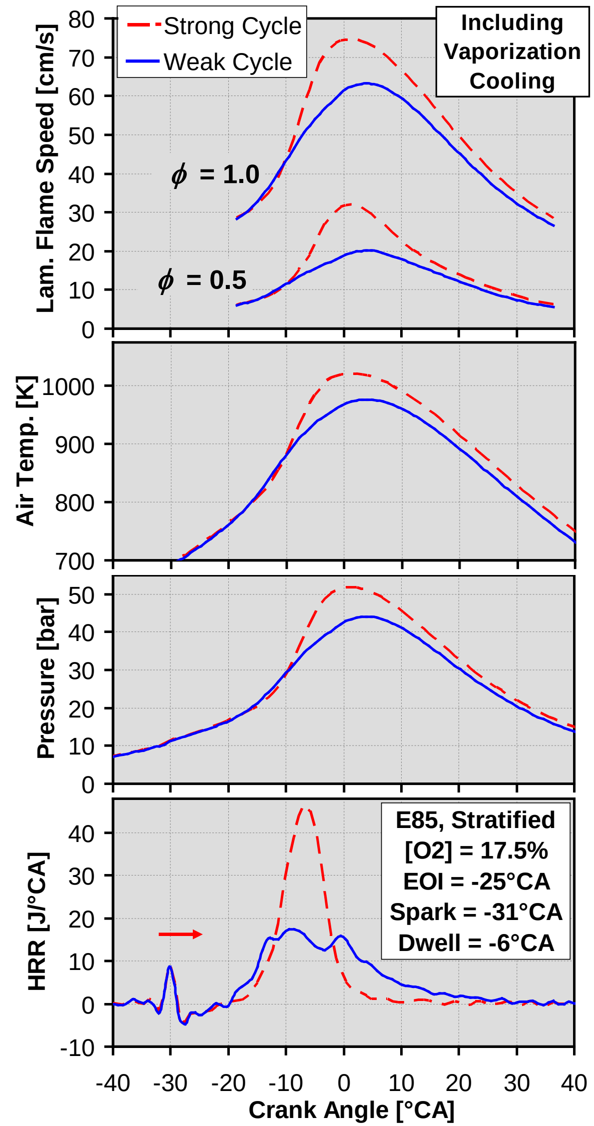


Understanding Slow Burns

- The laminar flame speed (S_L) is one of the major parameters that determine successful flame development.
- Flame modeling using CHEMKIN-PRO at engine-relevant conditions.
- Use Ethanol to represent E85.



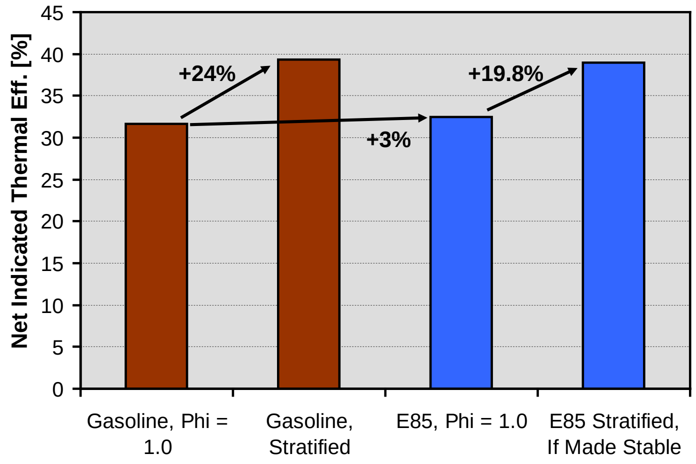
- Flame speed increases rapidly with temperature.
- Stoichiometric mixture has most robust flame.
- CA-resolved S_L shows that too-lean mixture is a potential cause of slow burn.
- Weak cycle has lower gas temperatures ahead of the flame.
  - Contributes to slow burn rate of too-lean mixtures.
- Need to apply optical diagnostics for complete understanding of slow burns for these conditions.



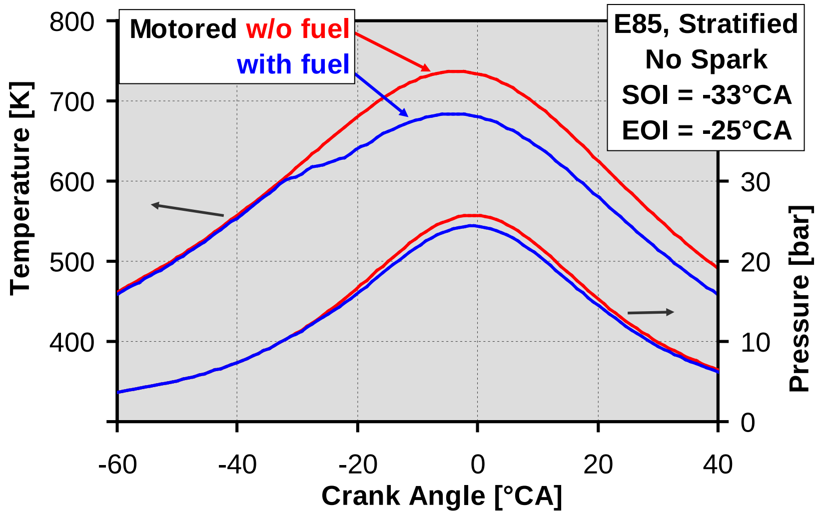
TE Improvement Comparison

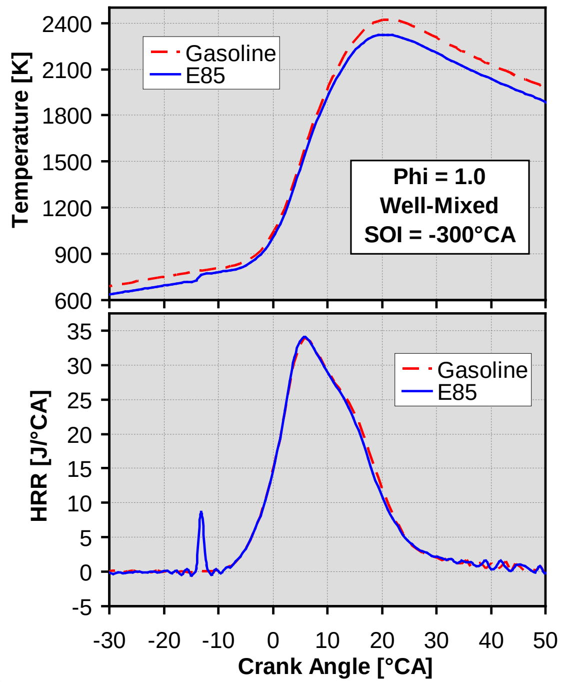
1. Even with improved combustion stability, TE improvement with stratified combustion would still be lower with E85 (19.8 vs. 24.0%).
2. Stoichiometric E85 operation has 3% higher TE.

- Both explained by strong vap. cooling with E85.
- For early injection, lower peak-combustion temperatures provide higher work-extraction efficiency. (Higher γ.)



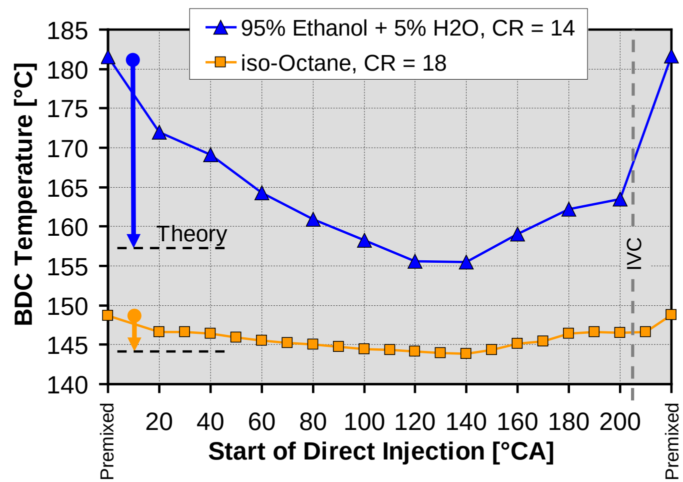
- E85 vaporization using valuable exergy near TDC hurts the thermal efficiency.

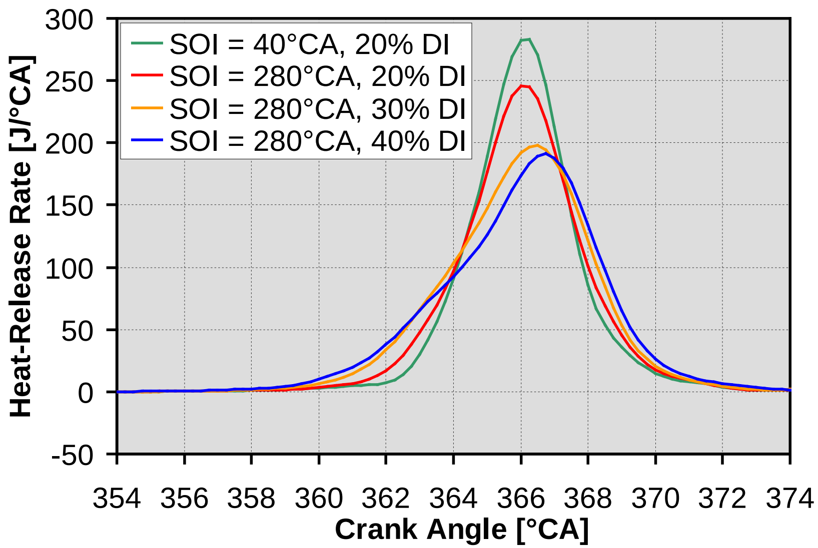


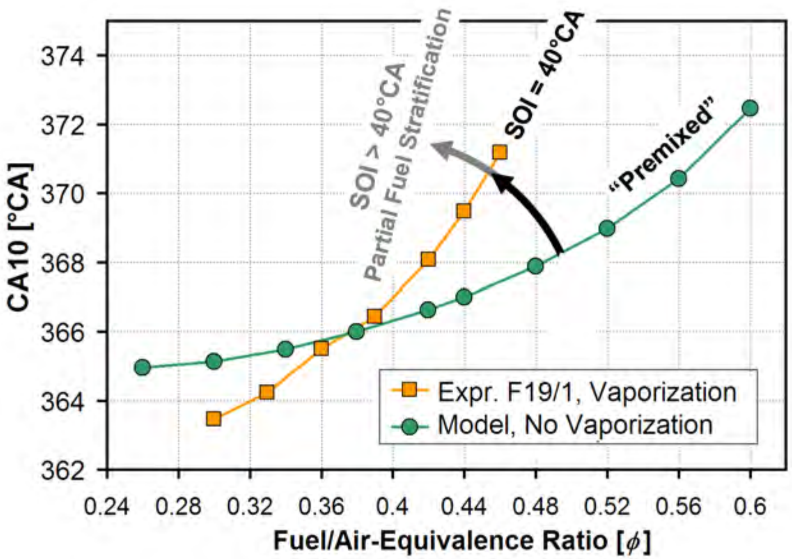


Ethanol HCCI Experiments

- Ethanol vaporization cooling is 5x greater than for iso-octane.
- Ethanol is a true single-stage ignition fuel.
  - Autoignition timing is sensitive to temperature.
- Vaporization cooling increases with ϕ, so CA10 retards strongly for DI.
- Use Partial Fuel Stratification (PFS) for strong reduction of peak HRR and PRR.

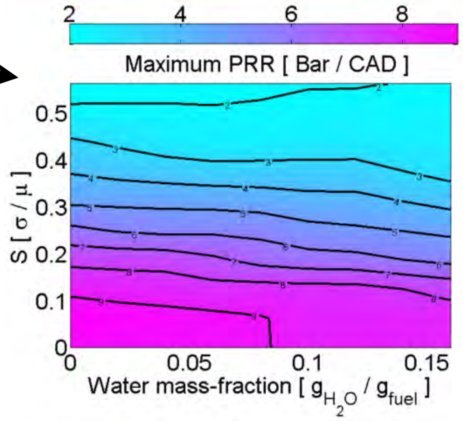






Collaborations / Interactions

- General Motors.
  - Hardware, discussion partner of results, and for development of diagnostics.
- D.L. Reuss (formerly at GM, now at UM).
  - Development of optical diagnostics for high-speed PIV and PLIF.
- 15 Industry partners in the Advanced Engine Combustion MOU.
  - Biannual meetings with 10 OEMs and 5 energy companies.
- Sandia – Biomass Conversion Team.
  - Discussions of potential biofuels and compatibility with engine combustion.
- Sandia HCCI Lab (J.E. Dec).
  - Reference HCCI autoignition data and PFS operation with ethanol.
- UNSW – Australia (E. Hawkes).
  - Multi-zone modeling of ethanol SCCI.
- UW-M (J. Brakora, R. Reitz).
  - KIVA-CFD.
- LLNL (W. Pitz) & Univ. of Galway (H. Curran).
  - Chemical-kinetics mechanisms.



Future Work FY 2011 – FY 2012

2011

- Make hardware alterations to allow deactivation of one valve to create swirl flow, and contrast with current tumble-flow results. Add intake air heater.
- Expand operating range with gasoline and E85 to include higher speeds and boosted operation. Study mid-range blends (~E40) for selected operating points.
- Discuss results with industry partners and decide on most relevant operating points to study optically.
- Install quartz windows for piston-bowl and pent-roof access.
- Finish the installation of laser-sheet imaging for high-speed PLIF and PIV.

2012

- Design and install full-quartz cylinder for better optical access.
- Apply optical diagnostics to identify the in-cylinder processes that are responsible for sporadic misfire cycles and partial burns.
  - Correlate variations in the flame growth with fuel concentration and flow field near spark, and with large-scale intake and compression flow field.
- Continue using CHEMKIN to investigate combustion fundamentals.
- Study fuel effects on both regular knock and low-speed preignition/superknock under highly boosted conditions.

Summary

- The new lab is contributing to the science-base for the impact of alternative fuel blends on advanced SI engine combustion.

- Using gasoline, lean stratified operation provides significant improvement of thermal efficiency.
- Improvements of TE are less with E85.
- Strong vaporization cooling for fuel injection near TDC hurts efficiency.
- Heat of vaporization is important factor that needs to be considered when pursuing future fuels.
- Cycle-to-cycle variations can be significant for low-NO_x operation.
  - More stable combustion would provide higher thermal efficiency.
- Development of high-speed optical diagnostics is nearly finished.
  - Apply to understand cyclic variability and propose ways to make more stable.
- Engine companies are encouraged to discuss the current project with us.
  - Welcome suggestions for both operating strategies and fuel blends.
- For HCCI, partial fuel stratification with ethanol offers potential to reduce peak HRR and lower PRR.
  - Vaporization cooling enhances the naturally occurring thermal stratification.

Technical Back-Up Slides

HCCI Experiments

- While DISI was being built, performed experiments in Dec's 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.**
  - **Partial fuel stratification using ethanol.**

SAE Paper 2010-01-0338 (engine speed, intake boost pressure, fuel/air equivalence ratio, charge temperature)

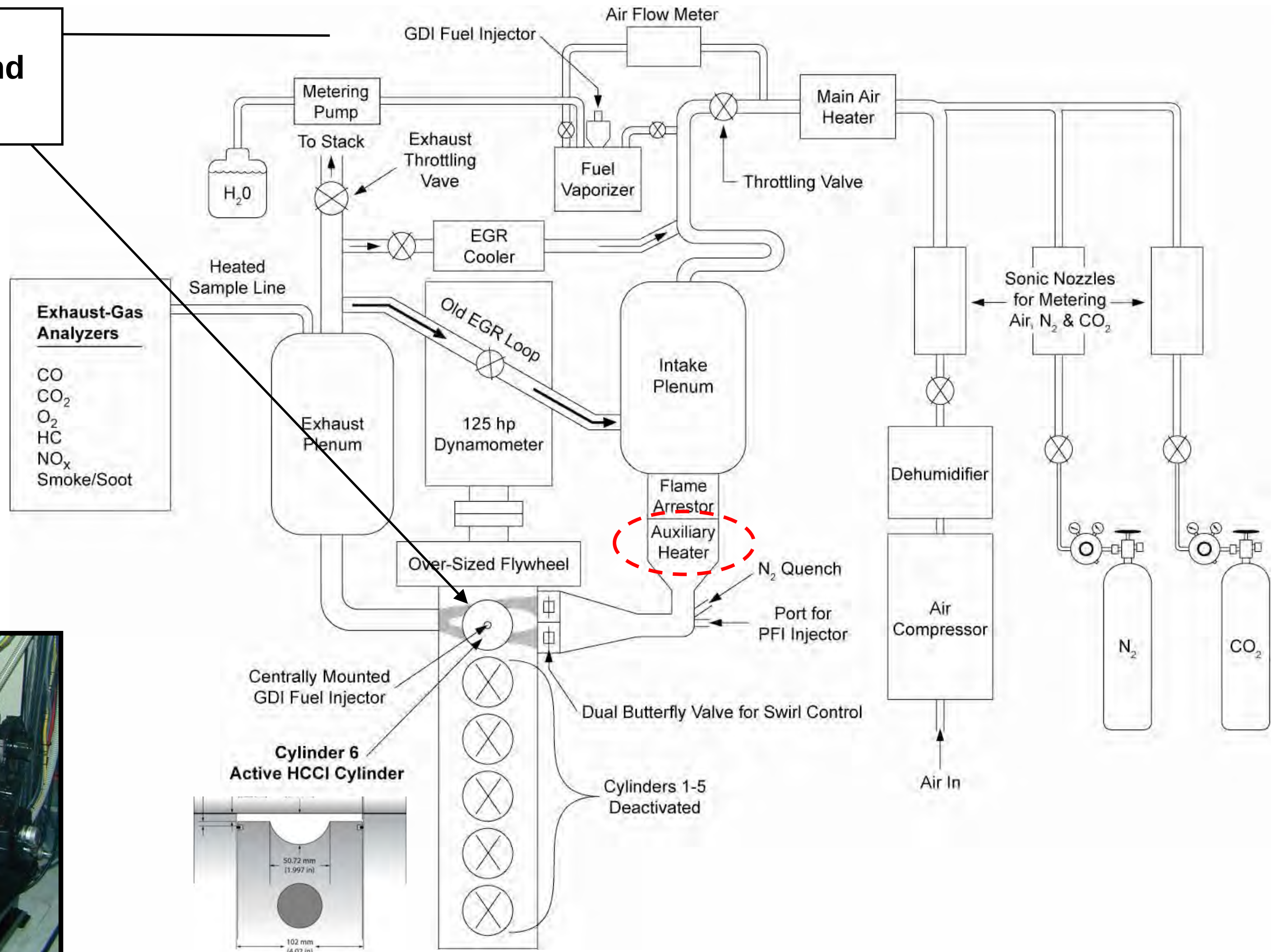
Combustion Symposium 2010 (EGR and constituents)

JSAE Paper for Kyoto meeting (vaporization cooling, partial fuel stratification using ethanol)

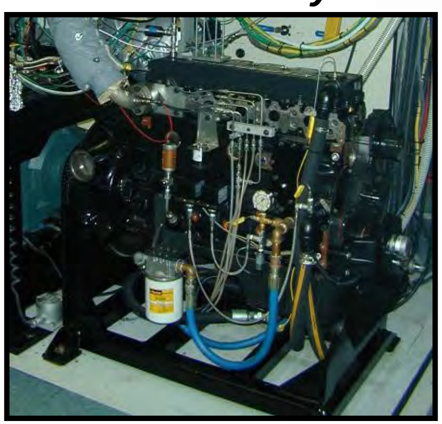
- Ethanol is a true single-stage fuel with minimal early heat release.
- Autoignition timing is sensitive to changes of temperature.
- Ethanol has very strong vaporization cooling.
- Partial-fuel stratification with ethanol therefore has potential to achieve an extended burn duration.
- Higher ϕ regions ignite last as those have more vaporization cooling.

All-metal HCCI Engine

Combine Premixed and DI Fueling



Cummins B
0.98 liter / cyl.

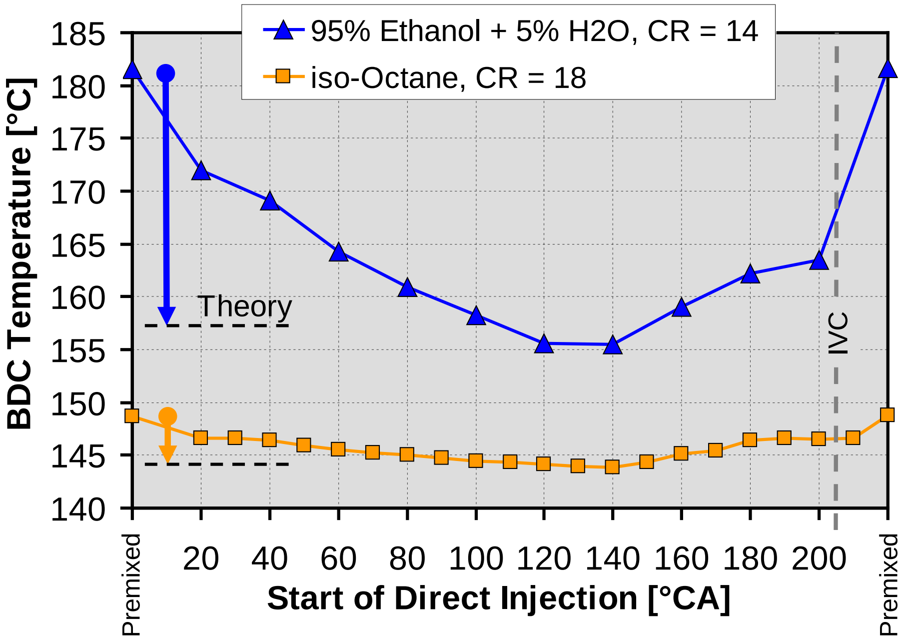


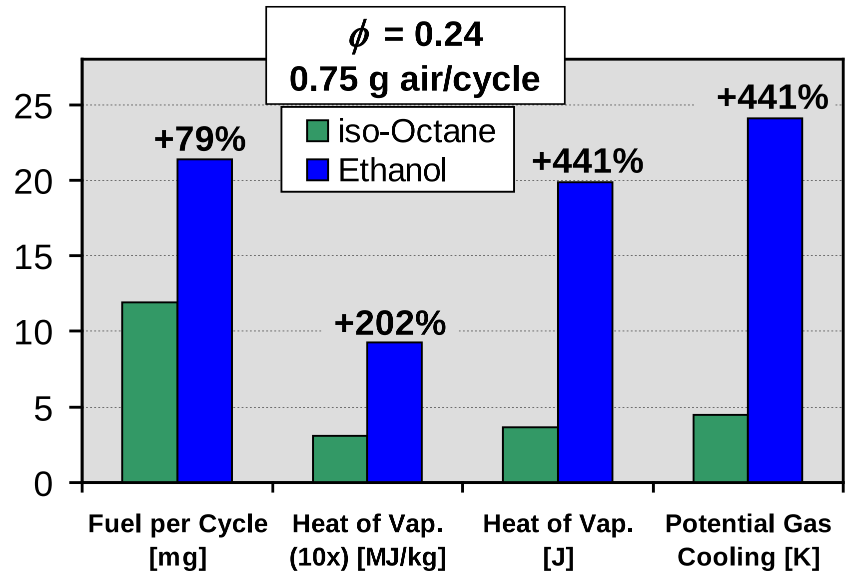
CR = 14

Vaporization Cooling

- Vaporization-cooling effects can be particularly strong for ethanol.

- Test 190 proof ethanol (95% ethanol, 5% water). "Worst-case scenario".
- Potential gas cooling is >5x that of iso-Octane.
- Observed cooling matches theory well.
- Maximum (observable) cooling effect occurs for SOI ~2/3 of intake stroke.
- Minimizes heat transfer from piston, so heat for vap. comes mostly from air.

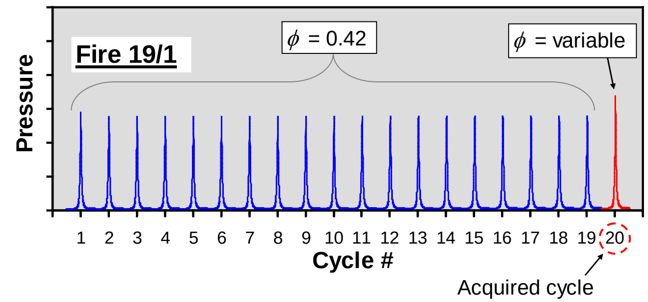


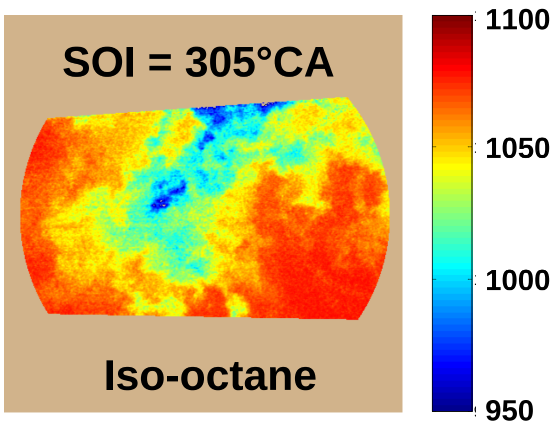


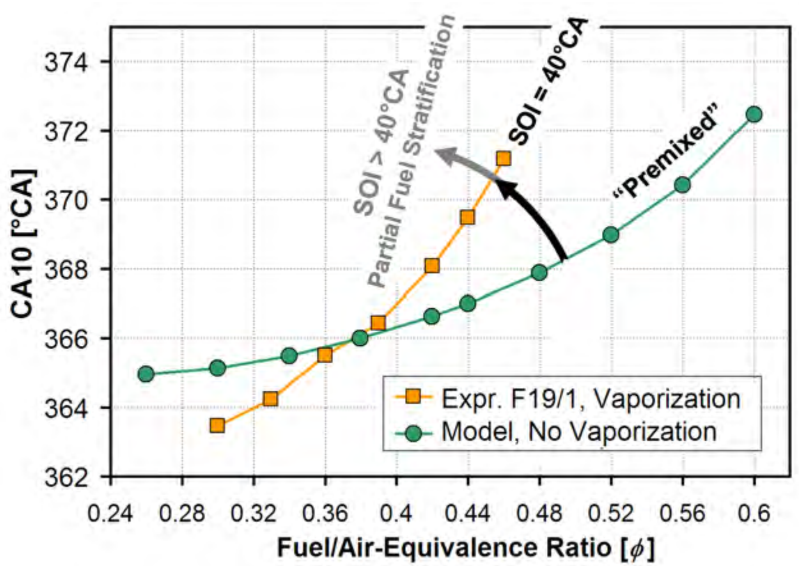
ϕ – Sensitivity / PFS

- Using a Fire-19/1 technique, both $T_{residuals}$ and T_{wall} are held constant.
- Quantify the combined effects of vap. cooling, γ and fuel-chemistry.
- ϕ-sensitivity becomes stronger than for premixed operation.
- SOI = 40 CA. Later SOI $\Rightarrow$ more cooling and higher ϕ-sensitivity.
- **Partial Fuel Stratification** (PFS) combines
  1. Premixing of most fuel with
  2. Late injection with remainder of fuel

  to achieve a staged combustion event.



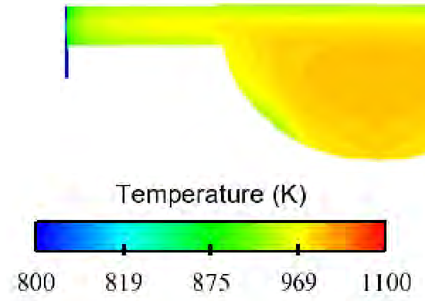




Hwang and Dec, SAE 2007-01-4130

PRR and HRR

- Lowest PRR is observed for SOI = 270 – 280°CA.
  - Decreases by 39%, from 9.8 to 6.0 bar/°CA (for 40%DI).
- Peak HRR is reduced, and more early HR as leanest zones ignite first.
- Shows that the thermal stratification has been enhanced.
- Response of PRR to SOI is complex.
- Fuel-vaporization cooling can counteract natural thermal stratification due to heat transfer.



KIVA-CFD by J. Brakora