Advanced Lean-Burn DI Spark Ignition Fuels Research

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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

- Inadequate data and predictive tools for fuel property effects on combustion and engine efficiency optimization.
- Evaluate new fuels and fuel blends for efficiency, emissions, and operating stability with advanced SI combustion.
  1. Lean, unthrottled DISI with spray-guided combustion.
  2. Dilute and mostly premixed charge with advanced ignition.

Budget

- Project funded by DOE/VT via Kevin Stork.
- FY12 - $750 K
- FY13 - $700 K

Partners / Collaborators

- PI: Sandia (M. Sjöberg)
- 15 Industry partners in the Advanced Engine Combustion MOU.
- General Motors - Hardware.
- D.L. Reuss (formerly at GM).
- W. Zeng (post-doc, Ph.D. on spray diag.)
- Sandia Spray Combustion (Pickett).
- LLNL (Pitz *et al.*) – Mechanisms and Flame-Speed Calculations.
- USC-LA (Egolfopoulos *et al.*) - Flame Measurements.
- USC-LA (Gundersen *et al.*) – Corona Ignition.

Objectives - Relevance

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

- Determining fuel characteristics that enable current and emerging advanced combustion engines that are as efficient as possible.

DISI with spray-guided stratified charge combustion system

- Has demonstrated strong potential for throttle-less operation for high efficiency.
- Overall lean operation prevents easy aftertreatment reduction of exhaust NO_x.
- High-EGR operation can reduce NO_x formation, but can also lead to partial burns.
- Stratified charge can easily cause soot formation.
- Hence, mastering NO_x / Soot / Combustion Stability trade-off is key to success.
- These processes are strongly affected by fuel properties (*e.g.* ethanol content).

- Develop a broad understanding of spray-guided SI combustion (*i.e.* conceptual model, including fuel effects).
  - For highest efficiency, cyclic variability needs to be minimized.
  - Help develop engineering tools that go beyond ensemble-averaged combustion, and incorporate cyclic variability.

- Current focus is on E85 and gasoline, and blends thereof.
  - Latest E85 specifications allow 51-85% ethanol by volume.
  - Flex-fuel vehicles need to function with 0 – 85% ethanol in the fuel tank.

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 over wide ranges of conditions to identify critical combinations of operating conditions and fuels.
  - Speed, load, intake pressure, EGR, and stratification level.
- Second, apply a combination of optical and conventional diagnostics to develop the understanding needed to mitigate barriers.
  - Include full spectrum of phenomena; from intake/compression flows, fuel injection, fuel-air mixing, spark development and ignition, to flame spread and burn-out.

Supporting modeling and experiments:

- Conduct chemical-kinetics modeling of flame-speed and extinction for detailed knowledge of governing fundamentals.
  - Collaborate on validation experiments and mechanism development.
- CFD modeling of spray penetration and mixing.

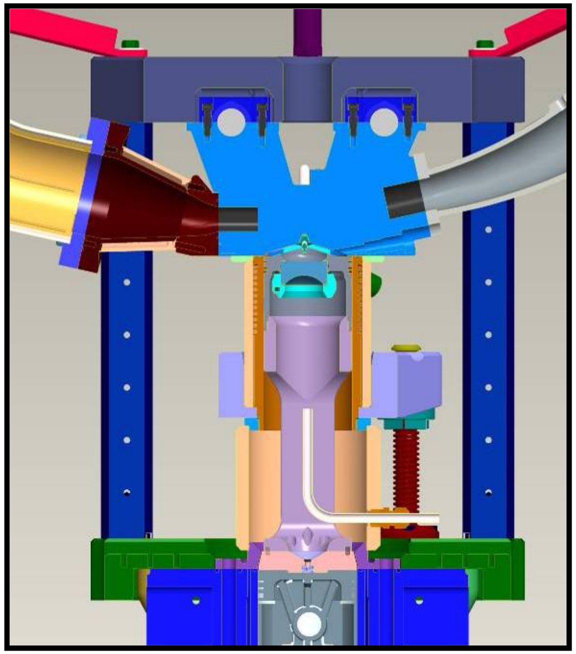
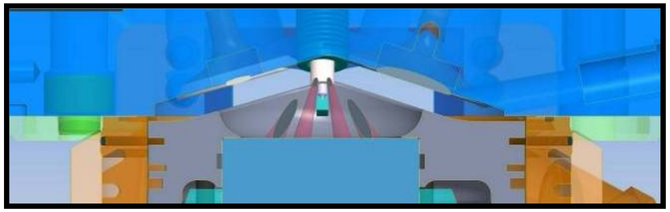
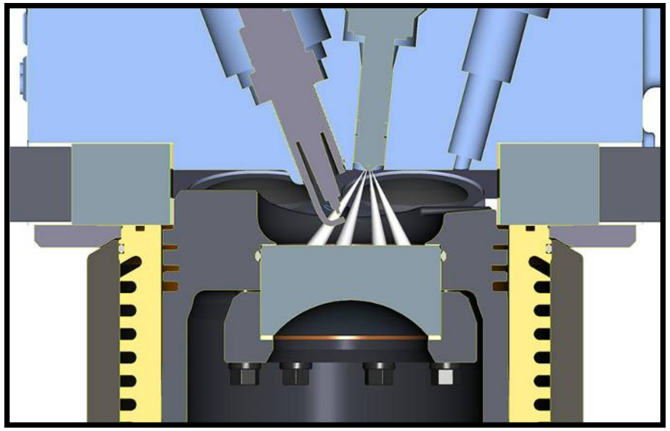
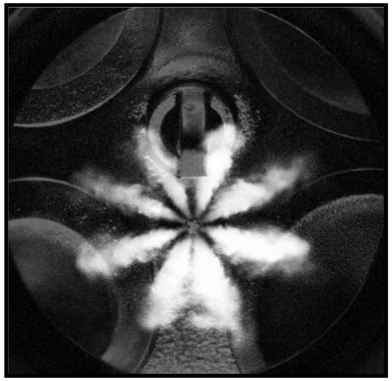
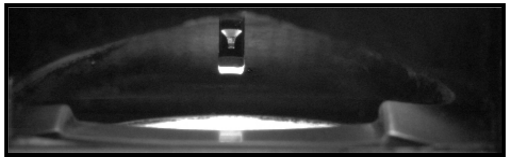
- Addresses barriers to high efficiency, robustness, and low emissions by increasing scientific knowledge base and enhancing the development of predictive tools.

Approach / Research Engine

Two configurations of drop-down single-cylinder engine.

Bore = 86.0 mm, Stroke = 95.1 mm, 0.55 liter swept volume.

- <u>All-metal:</u> Metal-ring pack and air/oil-jet cooling of piston.
- <u>Optical:</u> Pent-roof window, piston-bowl window, and 45° Bowditch mirror.
- Identical geometry for both configurations, so minimal discrepancy between performance testing and optical tests.
- 8-hole injector with 60° included angle $\Rightarrow$
  22° between each pair of spray center lines.
  Spark gap is in between two sprays.

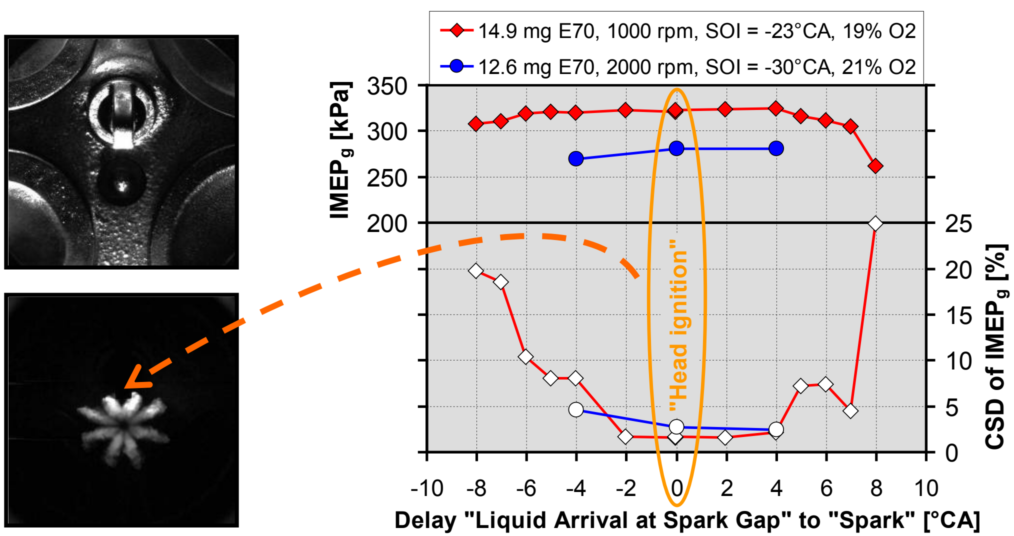







Technical Accomplishments

- Examined E85 operation with near-TDC fuel injection for ultra-low NO and soot.
  - Spectroscopic characterization of the various stages of ignition and combustion.
  - Effects of intake O_2 on exhaust soot emission.
  - Spark-plasma stretch analysis and dual-camera high-speed combustion luminosity imaging for understanding partial burn cycles.
- Performed PIV measurements of in-cylinder flows during compression, fuel injection and combustion.
- Compared NO formation for E85 and gasoline.
  - PIV measurements to understand mixing rates of hot combustion gases.
- Investigated effects of air flow (rpm & swirl) on well-mixed & stratified E70 oper.
  - Determined how the combustion rate scales with engine speed, and the effects of cyclic flow variability.
- Initial examination of effects of fuel blend (E0 to E100) on stratified operation.
  - Spark-timing requirement for stable ignition and low soot emissions.
  - Soot and NO exhaust emissions across load ranges for operation with "head ignition".
- Examined the potential of PLIF imaging of E85 using intensified high-speed camera.
- Set up and validated FORTÉ CFD-code to study fuel-jet penetration and mixing.
- For well-mixed operation, initialized study of fuel effects on endgas autoignition (knock).

Parameter Space

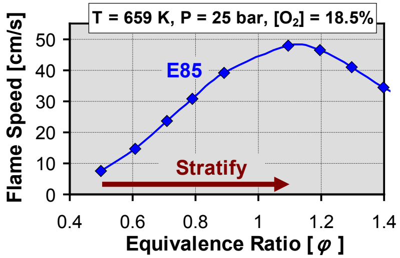
- The parameter space is huge.
- Grouped as hardware, static parameters & operating variables.
- Stratified operation for E70 and E85 often used spark timing (ST) for "head ignition".
- Stable combustion with good CA50 control.
- Head ignition can easily lead to unacceptable soot for gasoline.
  - Later spark is then needed (*i.e.* tail ignition).



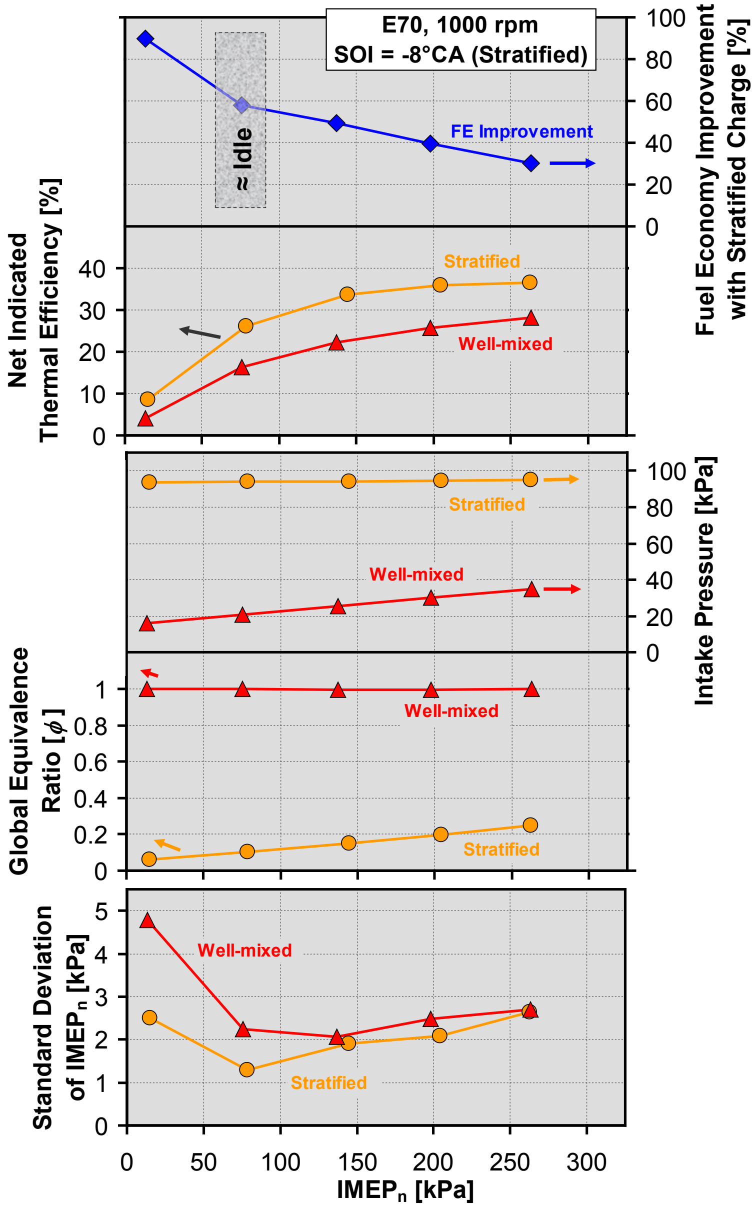
Parameter	This Presentation
CR	12
Piston Bowl	∅ 46 mm
Valve Timings	For Minimal Residual Level
Injector & Spray Targeting	Bosch 8 x 60° Straddling Spark
Swirl Index	2.7
Tumble Index	0.62
Injection Pressure	170 bar
# of Injections	Single
Spark Energy	106 mJ
$T_{coolant}$	60°C
T_{in}	26-28°C
$P_{exhaust}$	100 kPa
Fuel Type	Gasoline (E0) – E100
Engine Speed	1000 - 2000 rpm
Intake Pressure	18 - 105 kPa
$IMEP_n$	20 - 637 kPa
Start of Injection	-310 to -6°CA
Spark Timing	-36 to -5°CA
EGR / $[O_2]_{in}$	21 – 14.5% O_2

Fuel Economy Potential with Stratified Comb.

- Well-mixed lean mixtures burn too slowly for stable SI operation.

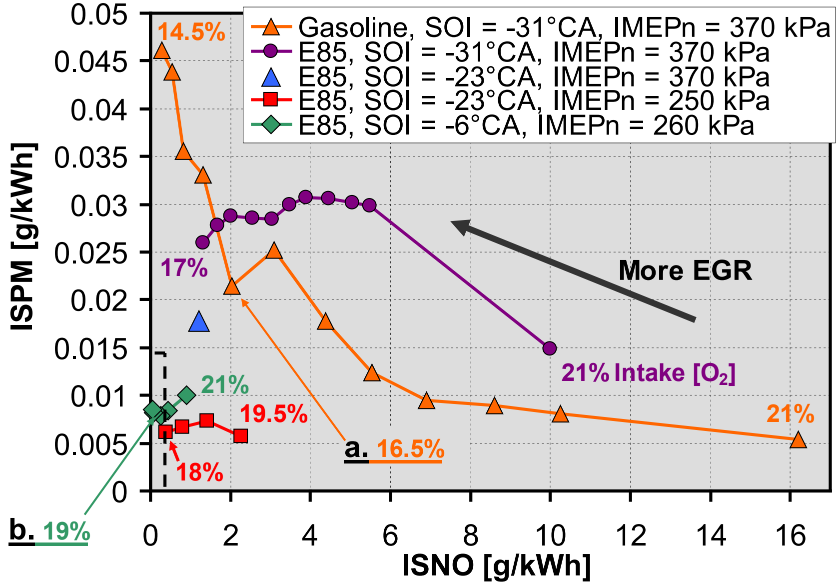


- Overcome this with fuel stratification to raise local ϕ.
- Allows lean and throttle-less engine operation.
  - High γ, and no pumping losses.
    $\Rightarrow$ High efficiency.
- Example for E70 fuel.
- Strongest gain of fuel economy for low loads.
  - 30% FE gain at ¼ load to 60% near idle.
- Overall lean operation prevents easy exhaust aftertreatment of NO_x.
- This example used "head ignition" of fuel jets.
- Head ignition allowed very small fuel injections to be combusted stably.

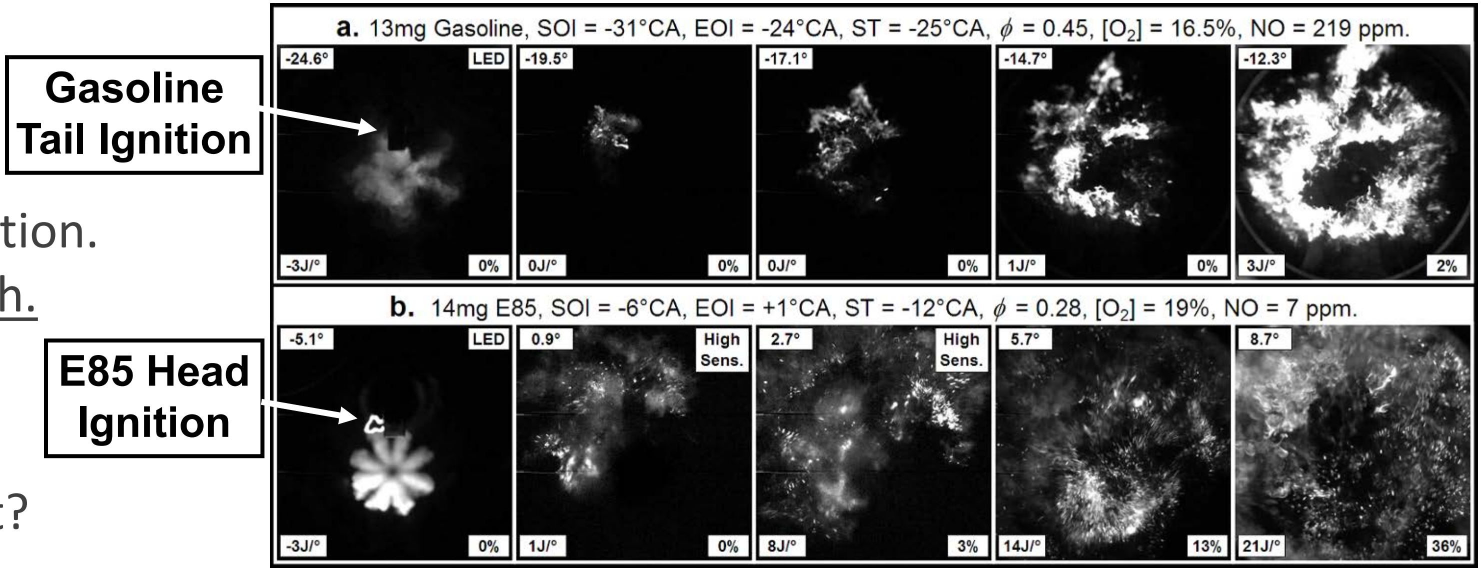


Previous Results - Reaching Inside NO/PM Box

- With E85, can reach inside the US2010 NO/PM box, <u>using near-TDC injection</u>.
- E85 responds favorably to SOI retard.
  - Lower peak temperatures, and less residence time, ⇓ NO formation.
- Oxygenated fuel, and strong vaporization cooling of ethanol.
  - Suppresses soot formation.

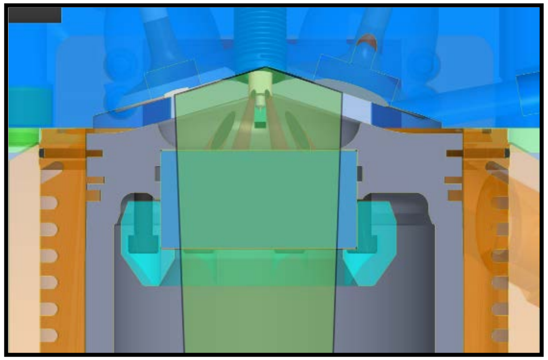


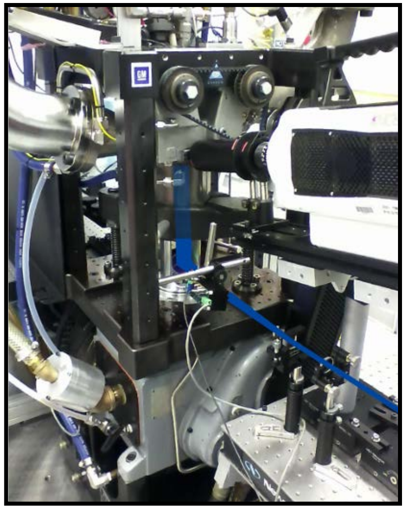
- Less flame-like combustion for E85 warrants further investigation.
- <u>Use spectrograph.</u>
- Nature of early faint flames?
- Presence of soot?

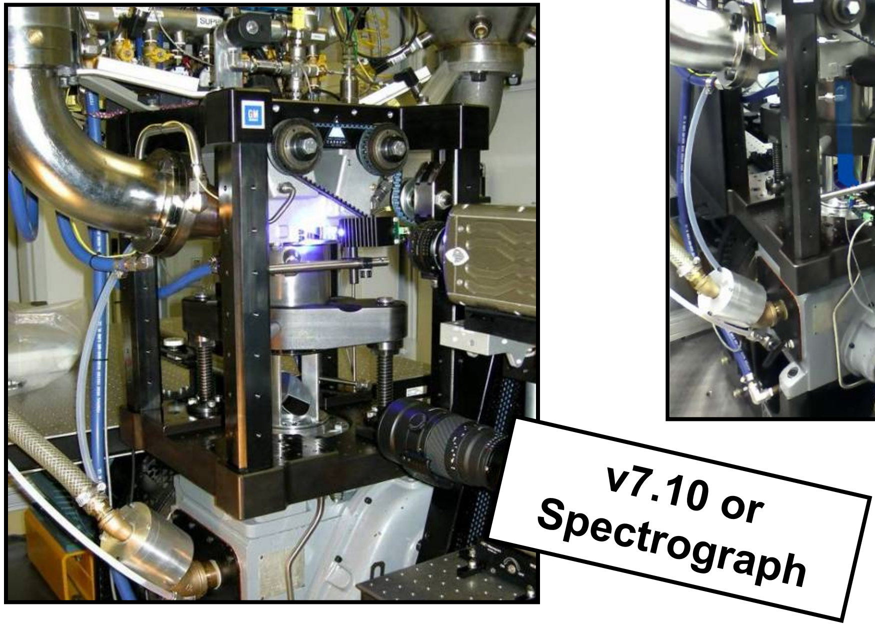


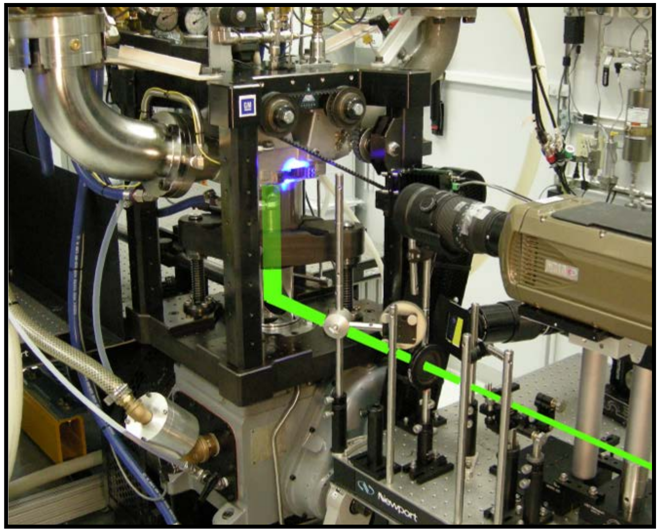
Optical Diagnostics Setups

- PLIF high-speed 355 nm laser – Quantronix HP-UV. Intensified Phantom v311.
- In-house developed pulsed high-intensity LED for Mie-scattering.
- PIV high-speed 532 nm laser - Quantronix Dual Hawk.
  - Vertical laser sheet near spark-plug gap.
- Mie & natural luminosity imaging via Bowditch mirror.
  - Notch filters to reject 532 nm laser light.
- Dual-camera setup or Spectrograph.



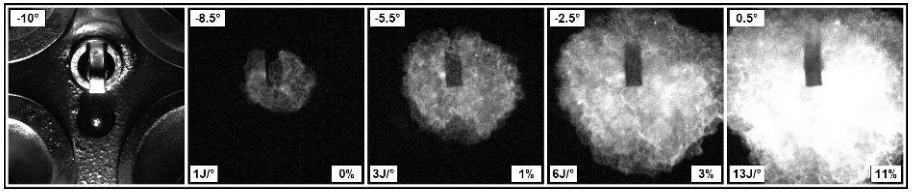


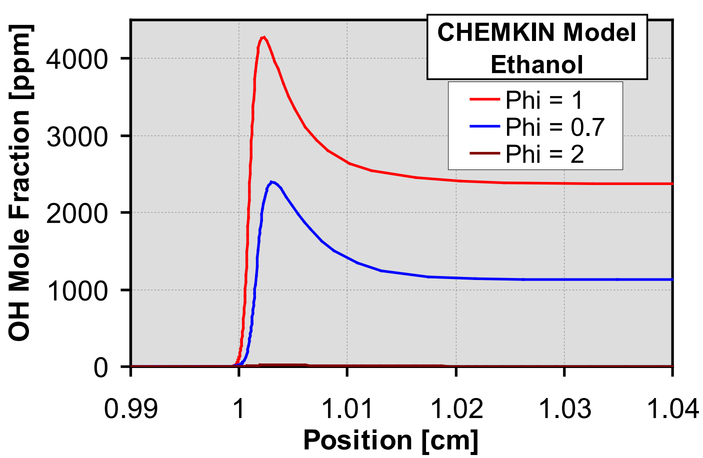


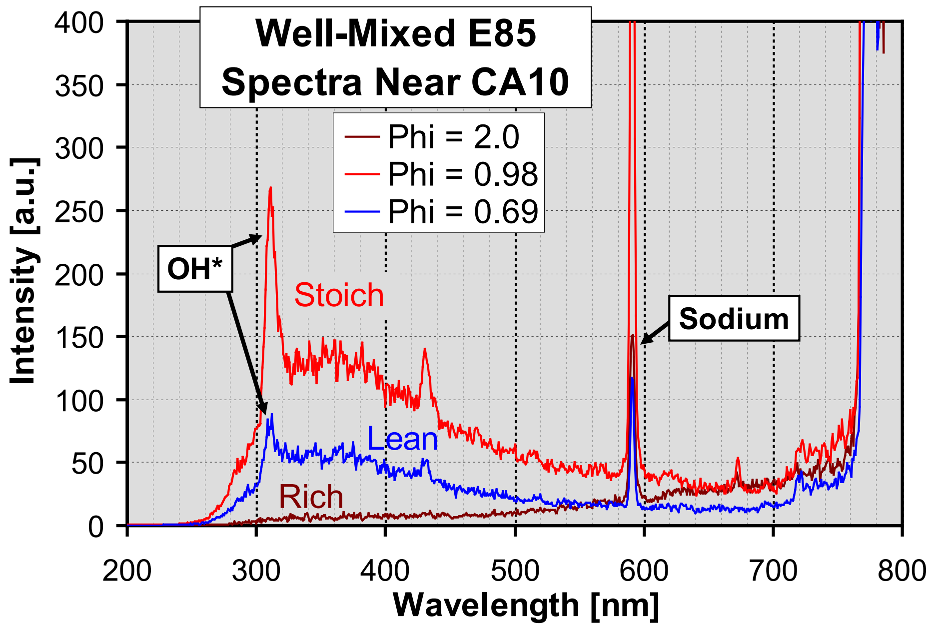


Well-mixed Spectral Response

- Spectrograph had coarse grating with 122 lines/mm.
  - Low resolution, but useful for obtaining an overview of the light characteristics.
- Emissions lines near 590 nm indicate high sodium content in fuel.
- Stoichiometric and lean operation show emissions peak near 308 nm.
  - Indicative of high levels of excited OH*.
- Spectra are consistent with CHEMKIN flame-modeling results.
- Rich combustion has weak luminosity and no peak near 308 nm.

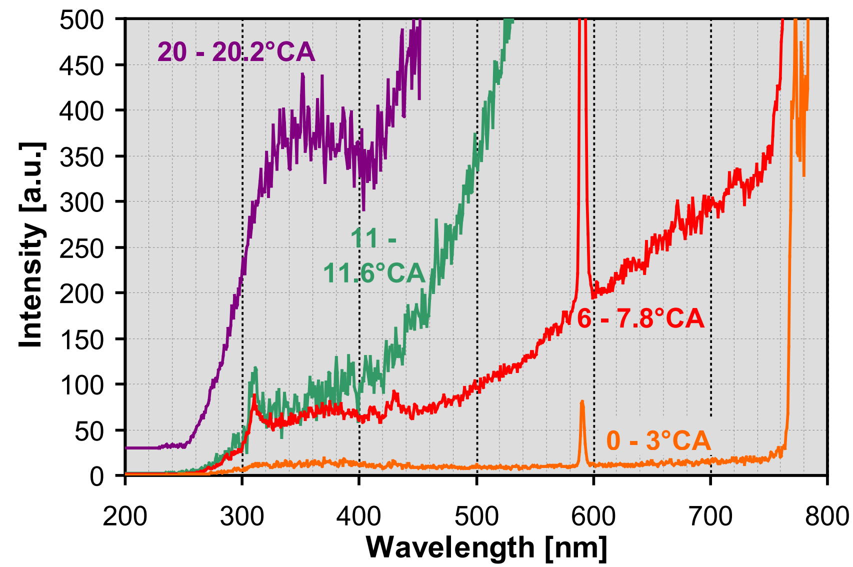


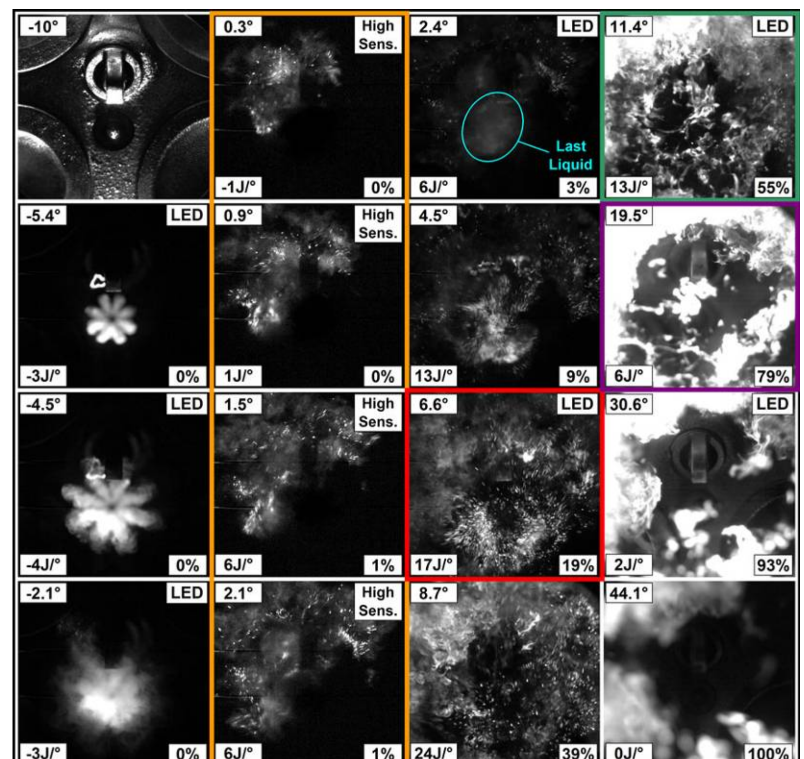


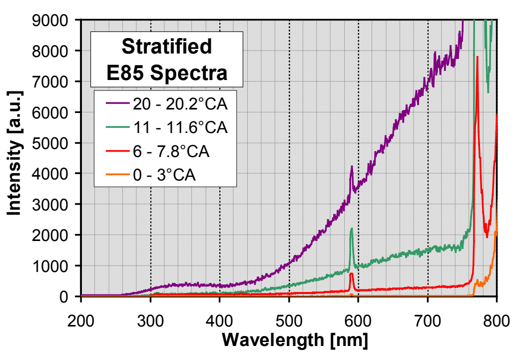


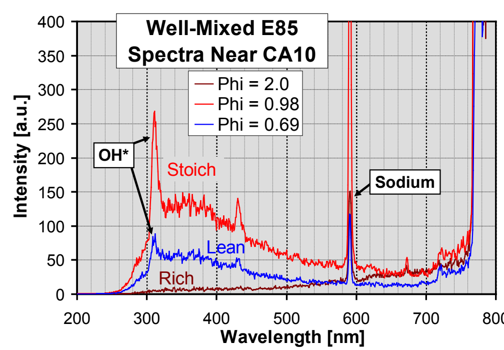
Stratified Spectra

- E85. SOI = -6°CA. Spark = -12°CA.
- Early luminosity is weak, and shows no peak around 308 nm.
  - Indicative of exclusively rich combustion.
- Hypothesis: Early flame is strained along fuel jets. Avoids extinction by existing in ϕ - regions with highest robustness.
- From 6° to 11° CA, distinct peak near 308 nm indicates stoichiometric and lean combustion.
- Late luminosity is dominated by black-body radiation, indicative of soot.



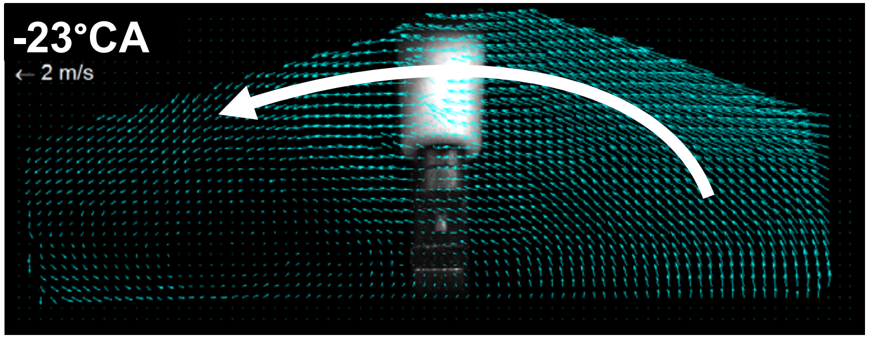


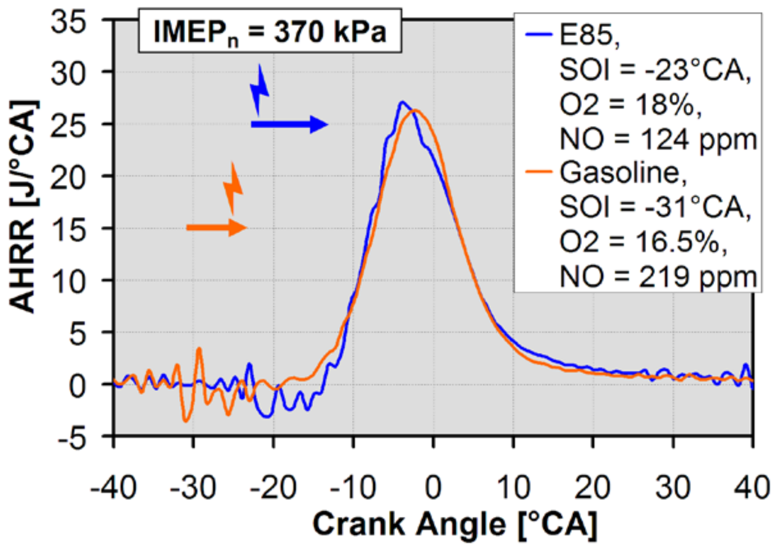




NO Emissions for Gasoline and E85

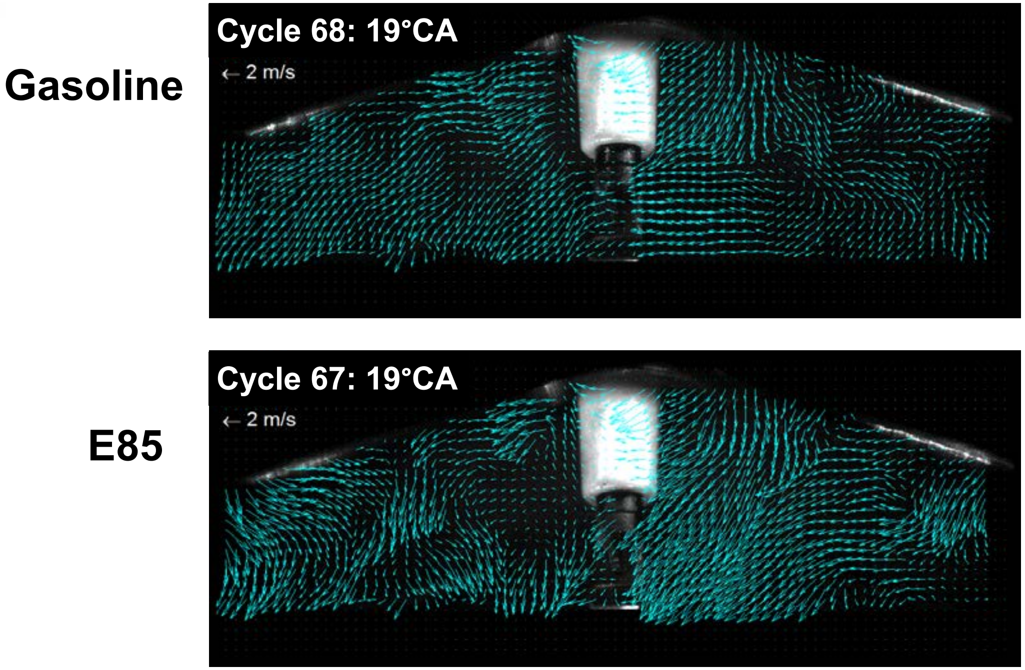
- Gasoline with SOI = -31°CA, and E85 with SOI = -23°CA have very similar AHRRs.
- Yet, NO emissions are 77% higher for gasoline (**219 vs. 124 ppm**). Why?
  - A. Intake $[O_2]$ is 1.5% lower for gasoline, so goes wrong way.
  - B. Spray model shows 60K more vaporization cooling for ethanol (at $\phi = 0.8$).
- With these factors, detailed gasoline/E85 surrogate mechanism by Dr. Marco Mehl at LLNL predicts **26K higher flame temperature** at $\phi = 0.8$ for E85.
- Hence, **other factors** must come into play as well to **limit NO formation**.
  - **C.** EOI to CA50 delay is 23°CA for gasoline but only 12°CA for E85. (Tail vs. Head Ignition).
  - **D.** E85 has 52% more fuel injected because of its lower heating value.
- **C & D** implications on in-cylinder mixing rates?
- Perform PIV measurements with and w/o fuel injection.
- Average non-DI PIV shows development of tumble flow in bowl.

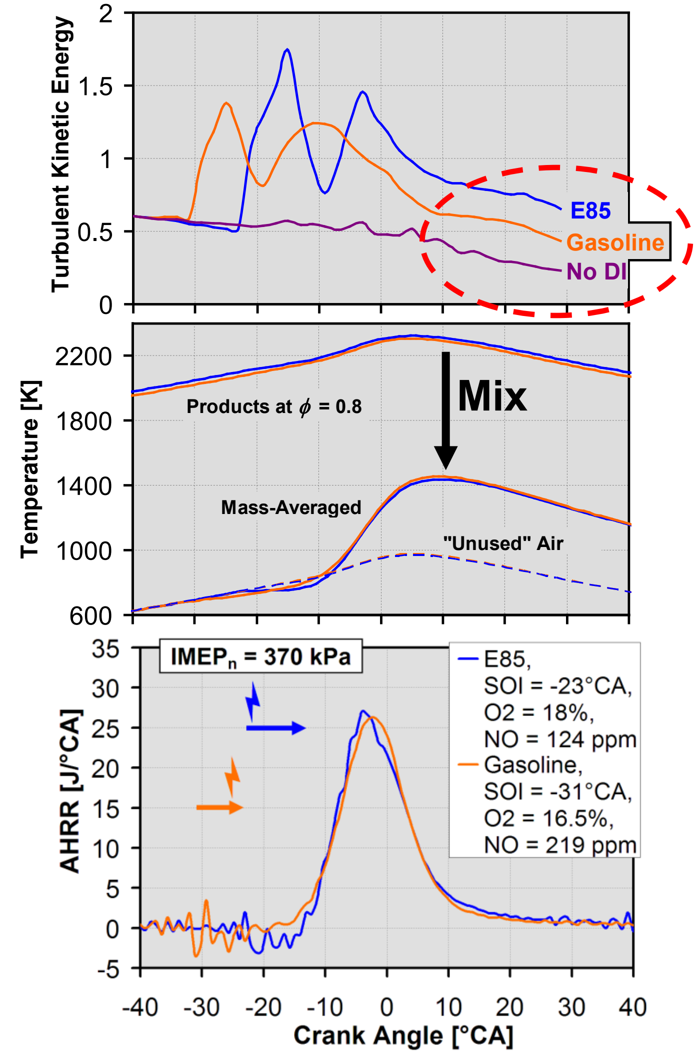




Mixing Rates Vs. NO Emissions

- PIV shows that in-cylinder turbulent kinetic energy is higher during burn-out for E85.
  - Lower heating value of E85 ⇒ 52% more fuel injected ⇒ More fuel-jet momentum.
  - More closely-coupled injection and combustion.





- Global ϕ = 0.43-0.45, so **more rapid mixing** of hot combustion products with cooler unused air has potential to stop thermal NO production.
- Consistent with E85's observed lower NO emissions.

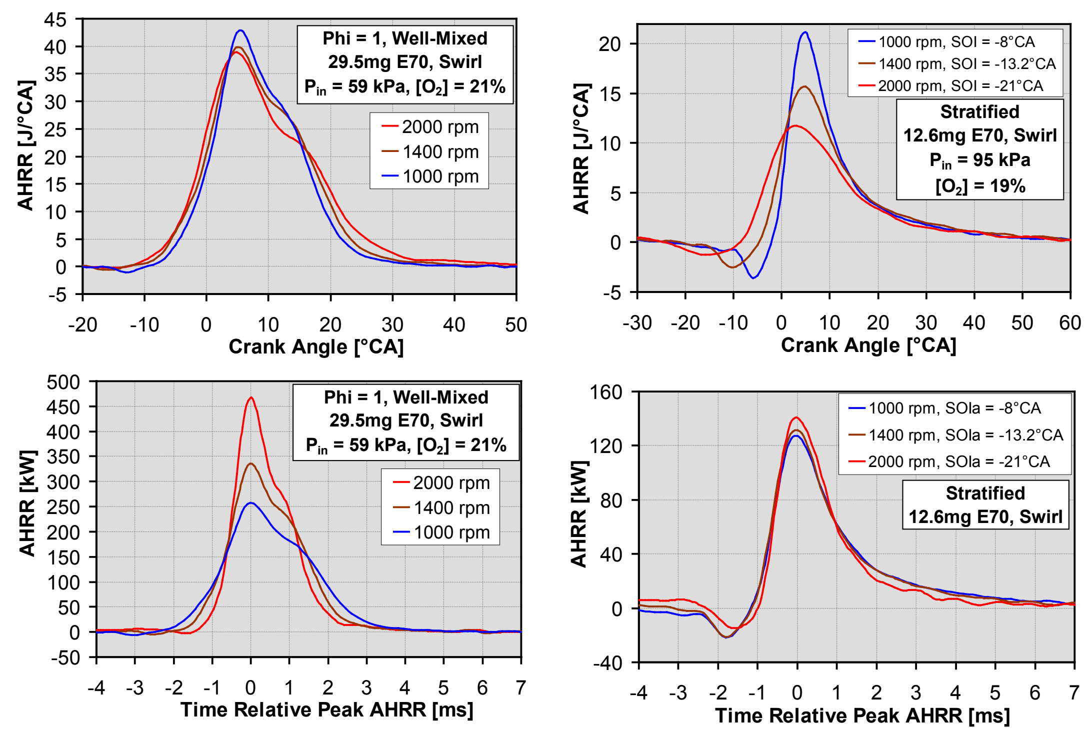
Role of In-Cylinder Flow Field

What is the role of the in-cylinder flow field for stratified-charge combustion?
  - The flow generated by the intake and compression strokes.

- Change the flow by **changing engine speed**.
- Observe AHRR changes. Well-mixed (WM) and stratified combustion.
- Well-mixed AHRR constant in **J/°CA**, stratified AHRR spreads out.
- WM-comb. speeds up in kW/ms. Combustion rate scales with turbulence level.

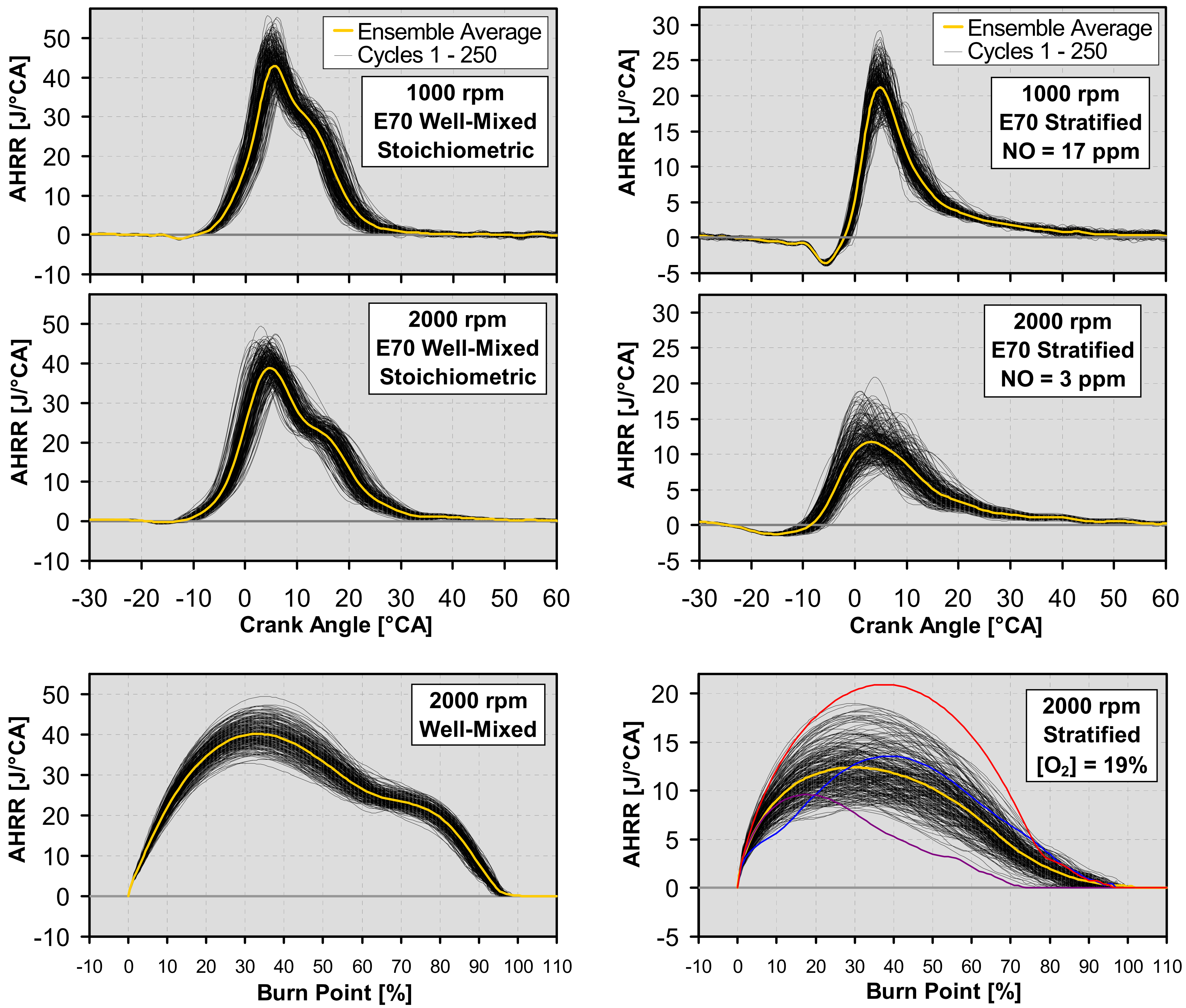
> - Stratified combustion rate constant in kW/ms.
> - Combustion rate governed by fuel/air mixing.
> - On average, this mixing is dominated by fuel-jet penetration.

- This is for E70 "head-ignition".
- "Tail ignition" more controlled by flame propagation?



In-Cylinder Flow Field vs. Cyclic Variability

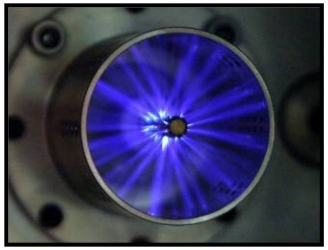
- Well-mixed operation: Relative cyclic variability does not change.
- Stratified combustion: rpm ⇑, in-cylinder flow field becomes sufficiently strong relative to the fuel jets ⇒ increased variability of combustion.
- CA50 variations make interpretation more difficult.
- Replot AHRR against % burn.
- WM shape is very repeatable.
- Stratified show large variability in burn profile.
- Less EGR stabilizes comb., but NO would increase.
- Keep EGR, but avoid slow and incomplete burns.

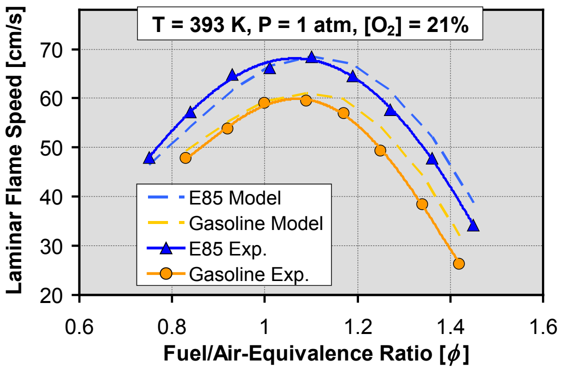


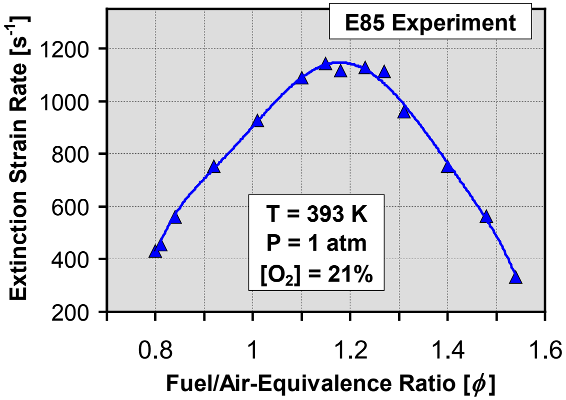
- Demonstrates need to go beyond averaged results.
- Continue study variability with multiple diagnostics.

Collaborations / Coordination

- General Motors.
  - Hardware, discussion partner of results, and for development of diagnostics.
- D.L. Reuss (formerly at GM, now at UM).
  - Development and interpretation of high-speed PIV and PLIF.
- 15 Industry partners in the Advanced Engine Combustion MOU.
  - Biannual meetings with 10 OEMs and 5 energy companies.
- LLNL (W. Pitz and M. Mehl).
  - Prediction of flame robustness for engine-conditions.
  - Development of chemical-kinetics mechanisms for gasoline-ethanol mixtures.
- USC-Los Angeles (Prof. Egolfopoulos) (not VT).
  - Flame speed and extinction measurements for gasoline/ethanol blends, and modeling.
- USC-Los Angeles (Prof. Gundersen) (not VT).
  - Corona Ignition.



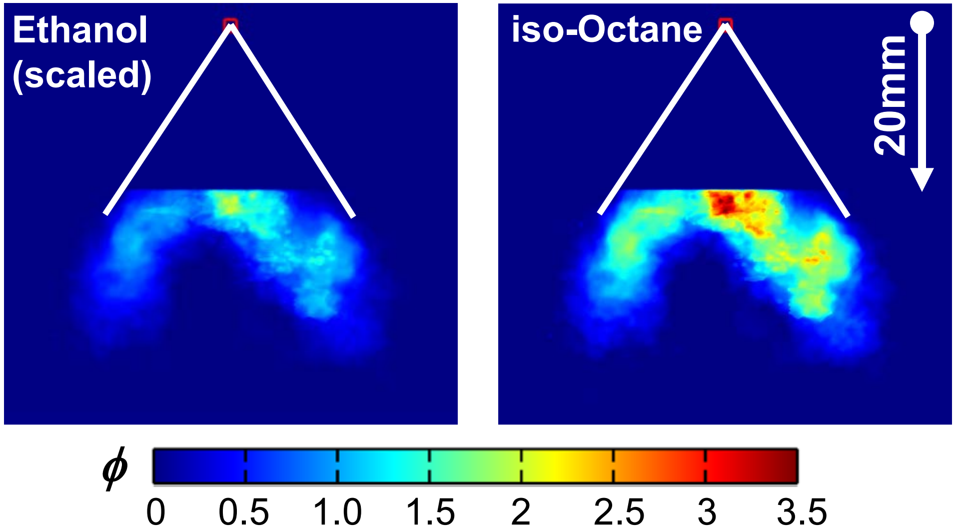




Collaborations (2)

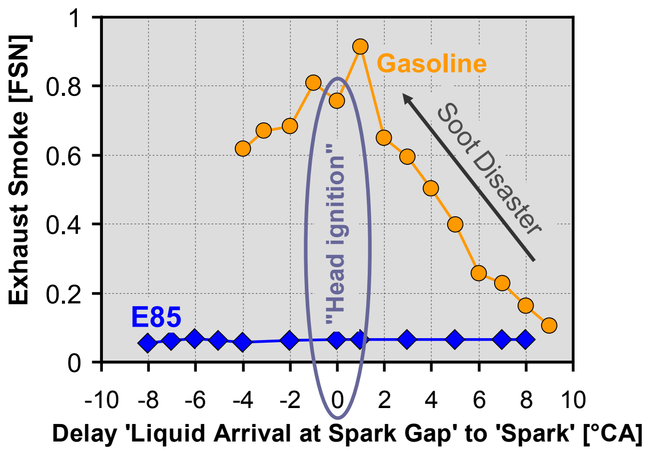
Sandia Spray Combustion (L. Pickett)

- Fuel effects on multi-hole sprays.
- Rayleigh-based measurement of fuel vapor for iso-octane.
  - Schlieren measurements indicate that air entrainment is very similar for ethanol.
- Rescale based on A/F_{st} to estimate differences in internal ϕ.
  - Iso-octane: up to $\phi = 3.5$ at 20mm from injector.
  - Ethanol: up to $\phi = 2$.



Project Accomplishments Cont.

- “Head Ignition” often provides stable operation with closely coupled injection and combustion.
  - Enables late SOI to drastically lower NO_x emissions.
- Typically, head ignition cannot be used for gasoline.
  - Spark needs to be retarded to allow rich regions to mix out and avoid “soot disaster”.



Future Work FY 2013 – FY 2014

- Continue PIV measurements of in-cylinder flows across speed ranges.
  - Examine relative strength of flow field and fuel jets.
  - Stratified operation with head and tail ignition.
- Study in detail interaction between flow field, spark plasma, and fuel jets.
  - Understand cyclic variability of stratified combustion for low-NO_x operation.
- Continue study effects of fuel blend (E0 to E100) on stratified operation.
  - Ignition stability, soot and NO_x exhaust emissions.
- Examine fundamental effects of charge temperature on stratified low-NO_x / soot operation with E85 and gasoline.
- Continue the development of the fuel-PLIF technique.
  - Apply PLIF to measure ϕ–fields for better understanding of fuel/air-mixing.
- Examine fuel-vaporization effects on thermal efficiency.
  - Boosted operation and high ethanol content.
- Continue using CHEMKIN to investigate flame-extinction fundamentals.
  - Provide better understanding of in-cylinder turbulence on flame quenching.
- Use FORTÉ CFD-code to study fuel effects on fuel-jet vaporization and mixing.
- Start examining the use of advanced ignition for lean/dilute combustion.

Summary

- This project is contributing to the science-base for the impact of alternative fuel blends on advanced SI engine combustion.

- Stable stratified operation was demonstrated to loads below idle.
  - Fuel economy improvement of **30% to 60%** relative throttled stoichiometric operation.

- Near-TDC fuel injection of E85 using "head-ignition" of fuel jets can enable very low exhaust NO and soot.
- Spectroscopic measurements indicate that **early E85 flames are exclusively rich**.
  - Consistent with measurements of flame-extinction rates of same E85 fuel.

- With similar heat-release, **NO emissions are much lower for E85** than for gasoline.
- PIV measurements show that E85's short delay from injection to combustion and more injected fuel together lead to **higher turbulence level during burn-out**.
  - Should contribute to limit thermal NO formation through mixing with cooler unused air.

- **Well-mixed and stratified operation respond very differently to changes of rpm.**
- Well-mixed HRR in kW scales directly with engine speed via increased turbulence.
- On average, stratified HRR in kW remains invariant to increased engine speed.
- Stronger intake and compression flows at higher rpm lead to increased variability of stratified combustion.