SAND2013-2418P

Advanced Lean-Burn DI Spark Ignition Fuels Research

Magnus Sjöberg

Sandia National Laboratories

May 16th, 2013

Project ID: FT006

Acknowledgement

This work was performed at the Combustion Research Facility, Sandia National Laboratories, Livermore, CA. Support was provided by the U.S. Department of Energy, Office of Vehicle Technologies via Fuels Technologies program manager Kevin Stork. Sandia is a multiprogram laboratory operated by the Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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.

<u>Supporting modeling and experiments:</u>

- 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.

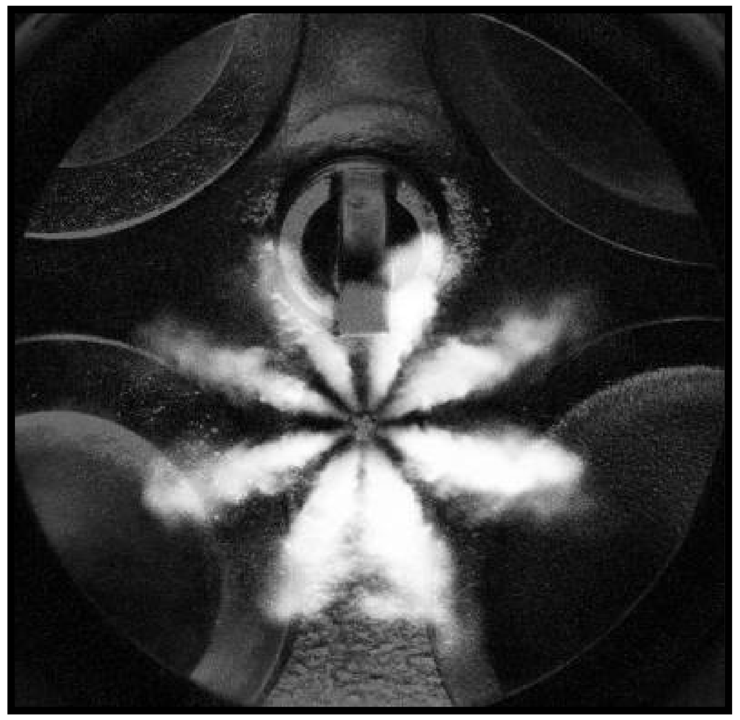
- Addresses barriers to high efficiency, robustness, and low emissions by increasing scientific knowledge base and enhancing the development of predictive tools.

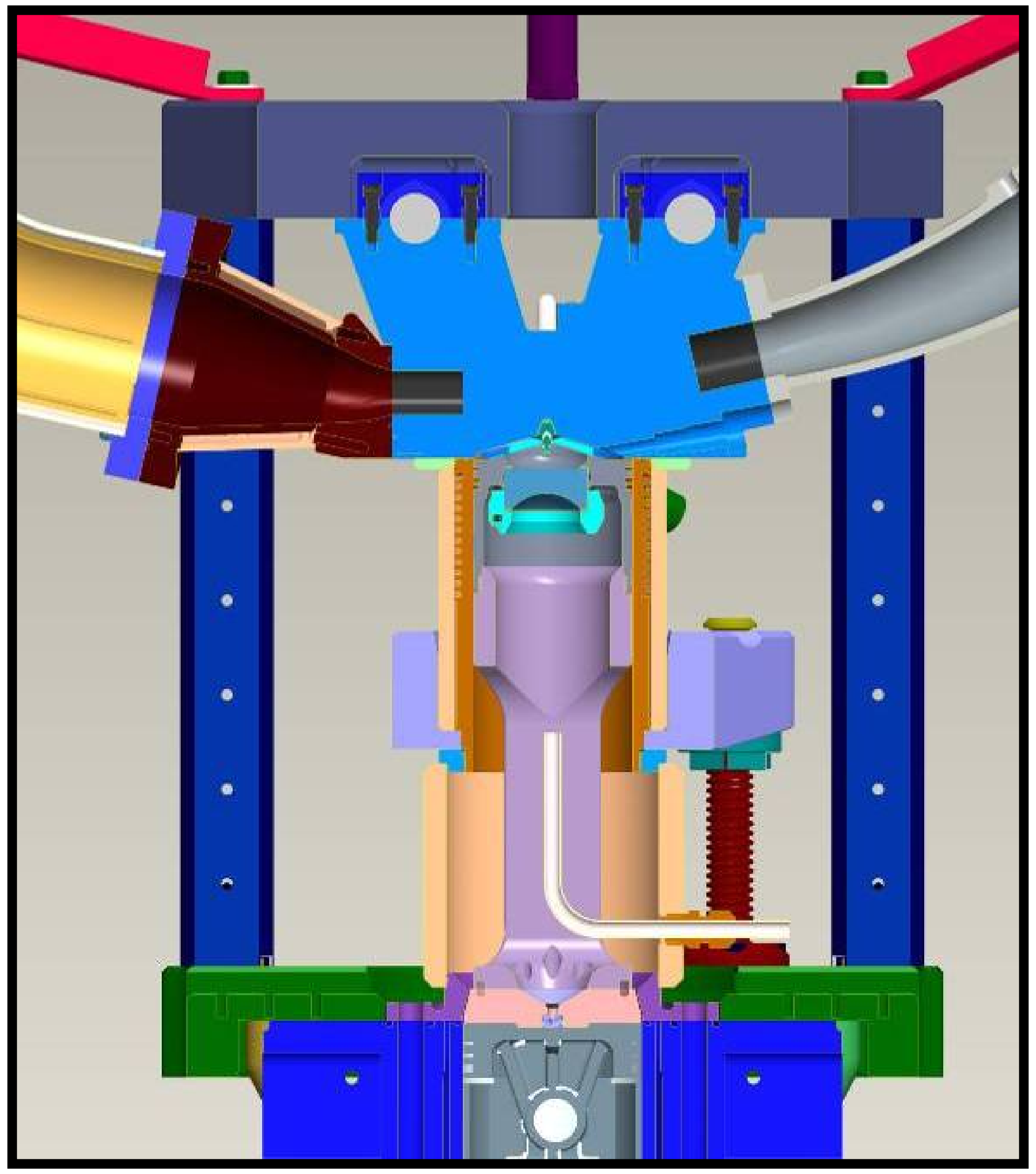
Approach / Research Engine

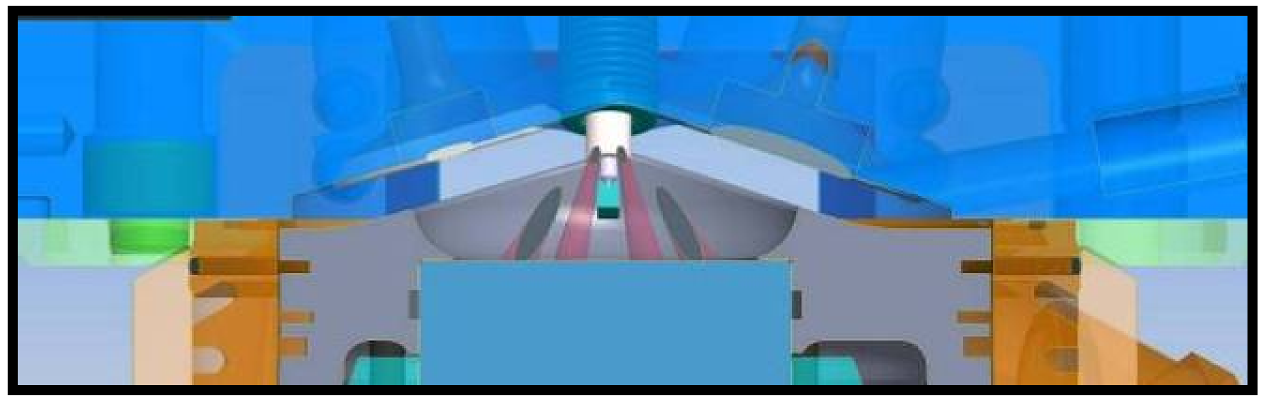
Two configurations of drop-down single-cylinder engine.

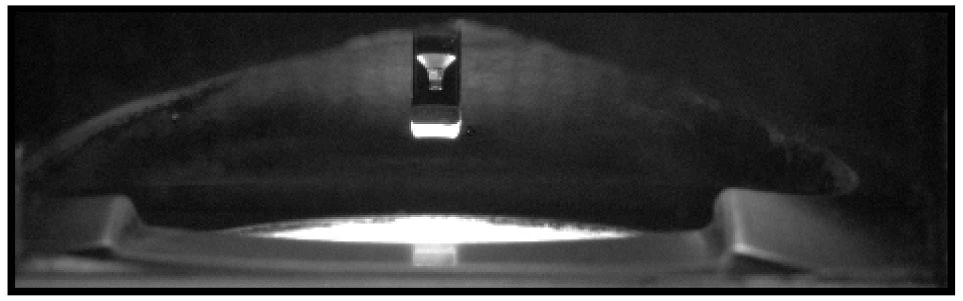
Bore = 86.0 mm, Stroke = 95.1 mm, 0.55 liter swept volume.

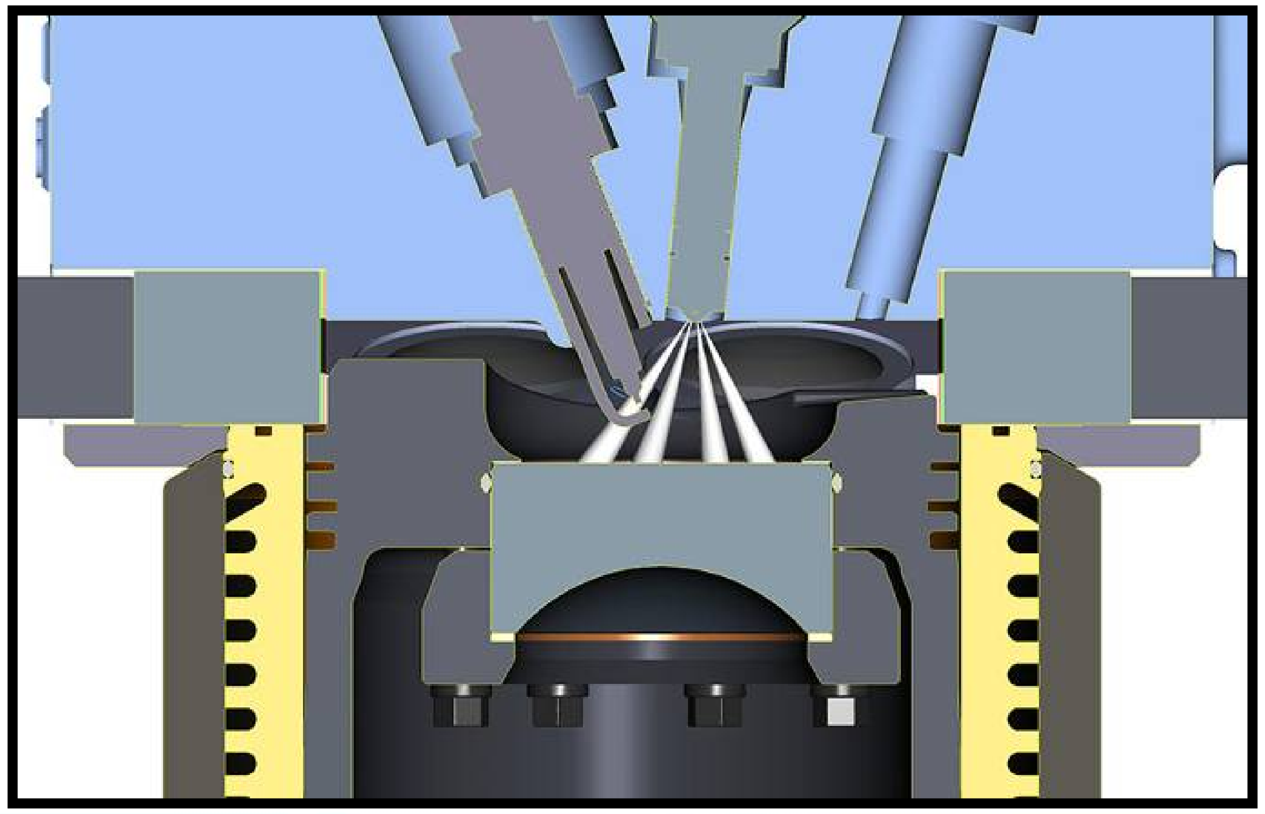
- <u>All-metal:</u> Metal-ring pack and air/oil-jet cooling of piston.
- <u>Optical:</u> Pent-roof window, piston-bowl window, and 45° Bowditch mirror.
- Identical geometry for both configurations, so minimal discrepancy between performance testing and optical tests.
- 8-hole injector with 60° included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

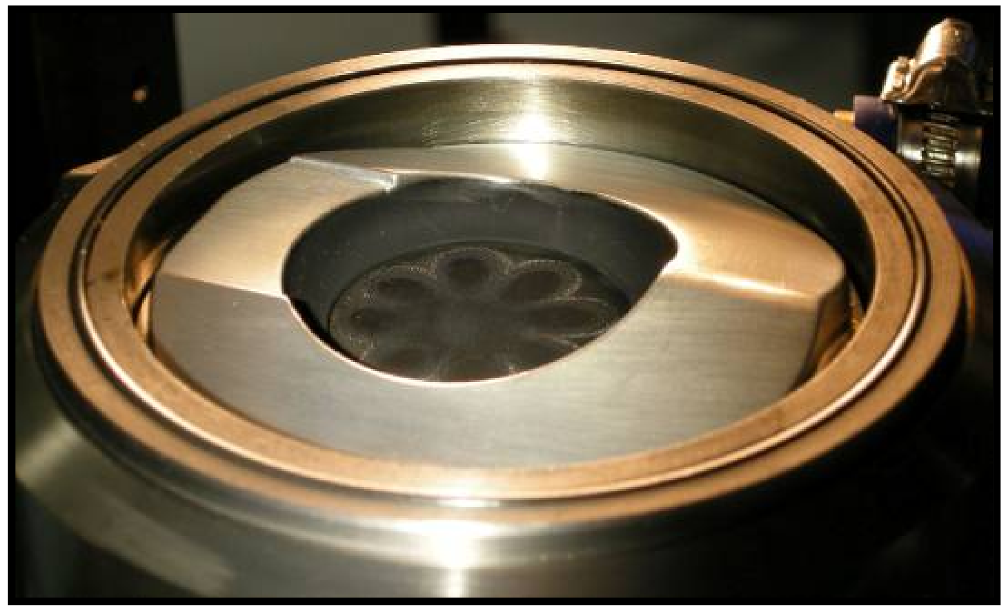










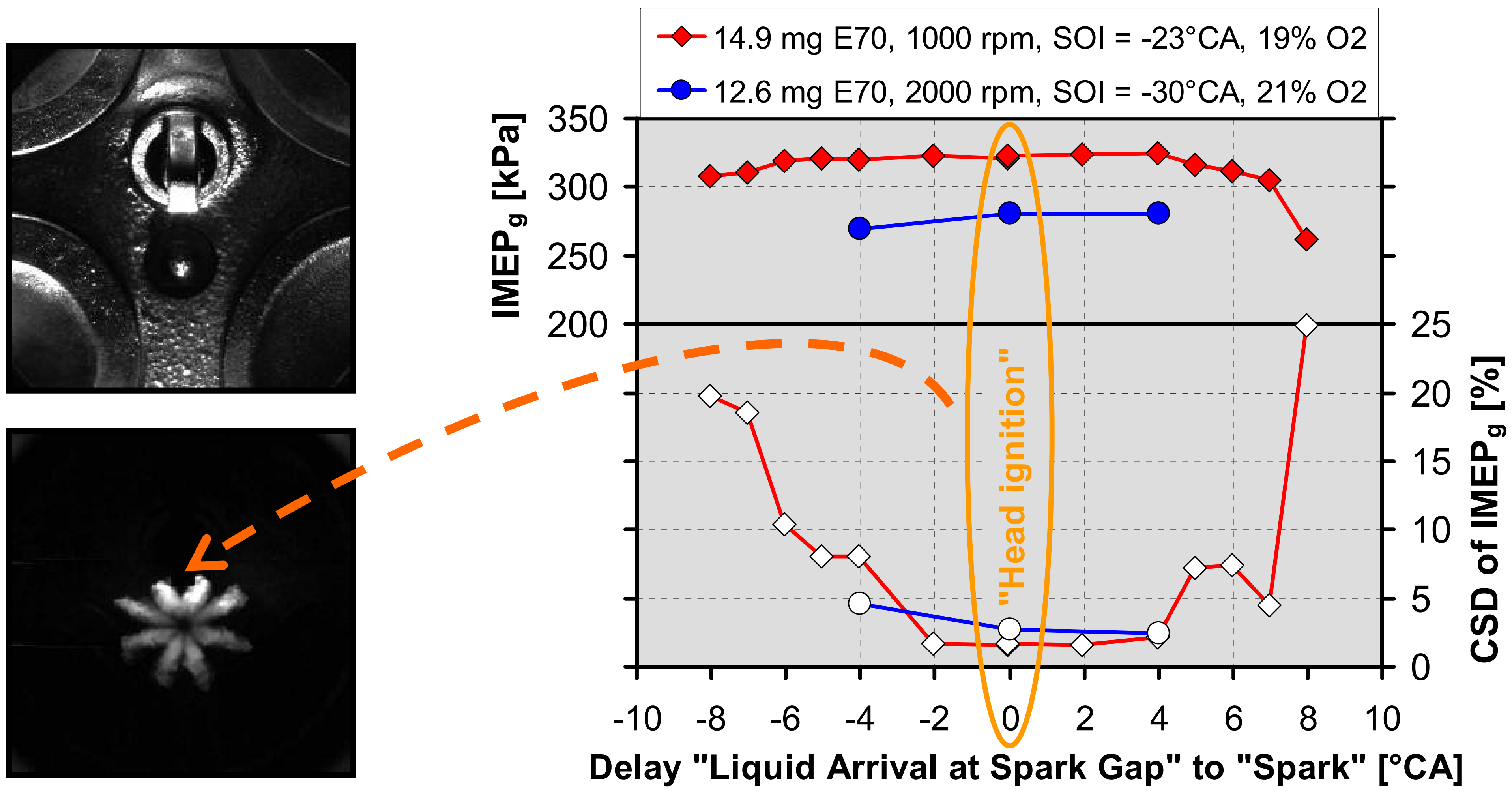


Technical Accomplishments

- 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

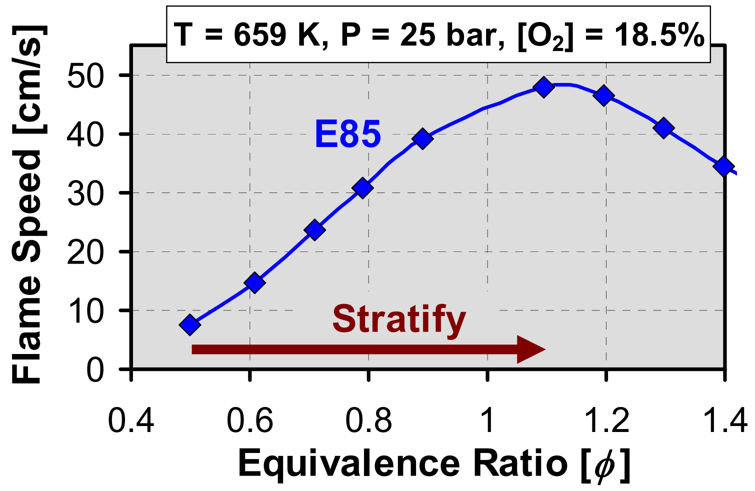
- The parameter space is huge.
- Grouped as hardware, static parameters & operating variables.
- Stratified operation for E70 and E85 often used spark timing (ST) for “head ignition”.
- Stable combustion with good CA50 control.
- Head ignition can easily lead to unacceptable soot for gasoline.
  - Later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



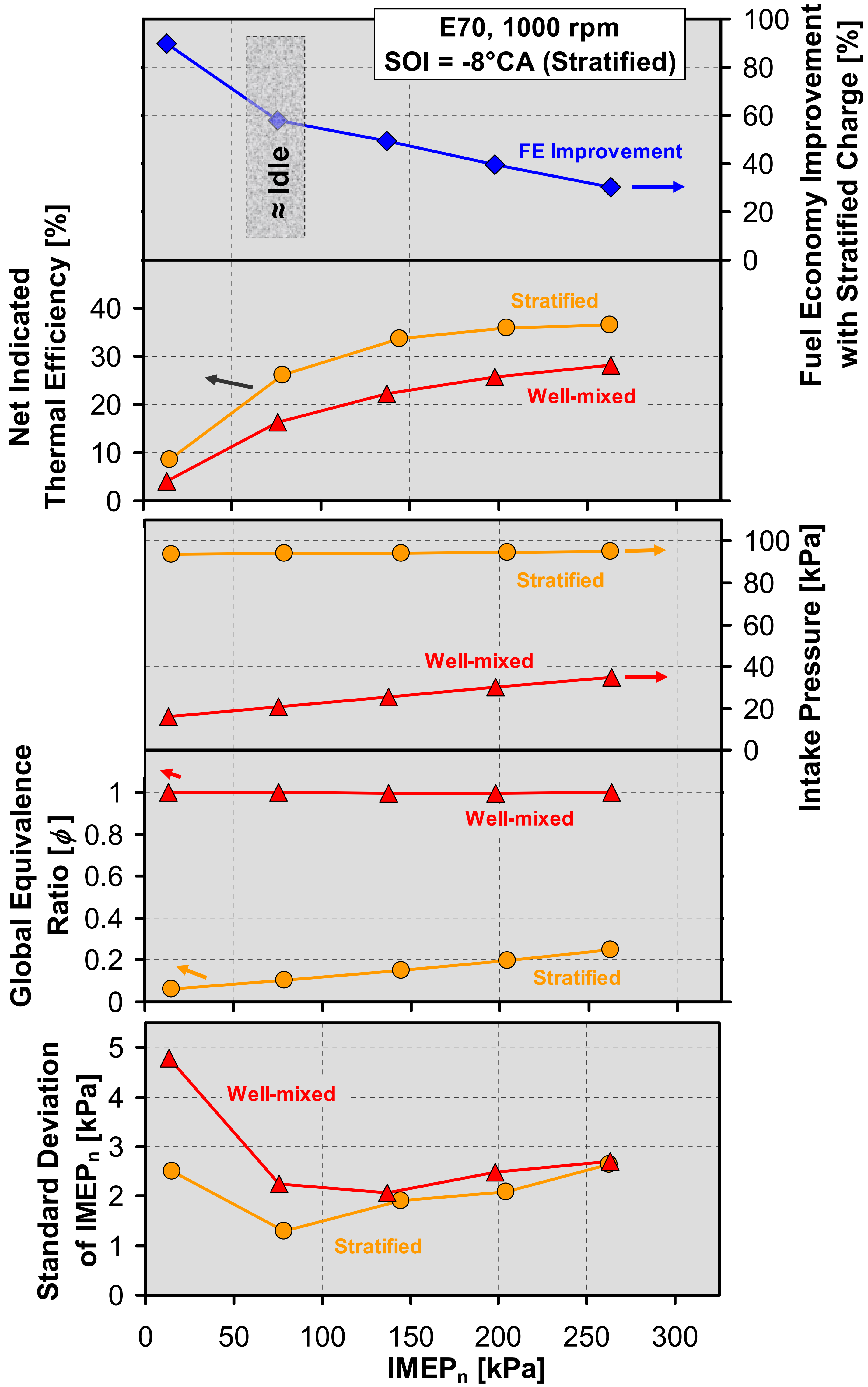
Parameter	This Presentation
CR	12
Piston Bowl	∅ 46 mm
Valve Timings	For Minimal Residual Level
Injector & Spray Targeting	Bosch 8 x 60° Straddling Spark
Swirl Index	2.7
Tumble Index	0.62
Injection Pressure	170 bar
# of Injections	Single
Spark Energy	106 mJ
$T_{coolant}$	60°C
T_{in}	26-28°C
$P_{exhaust}$	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.

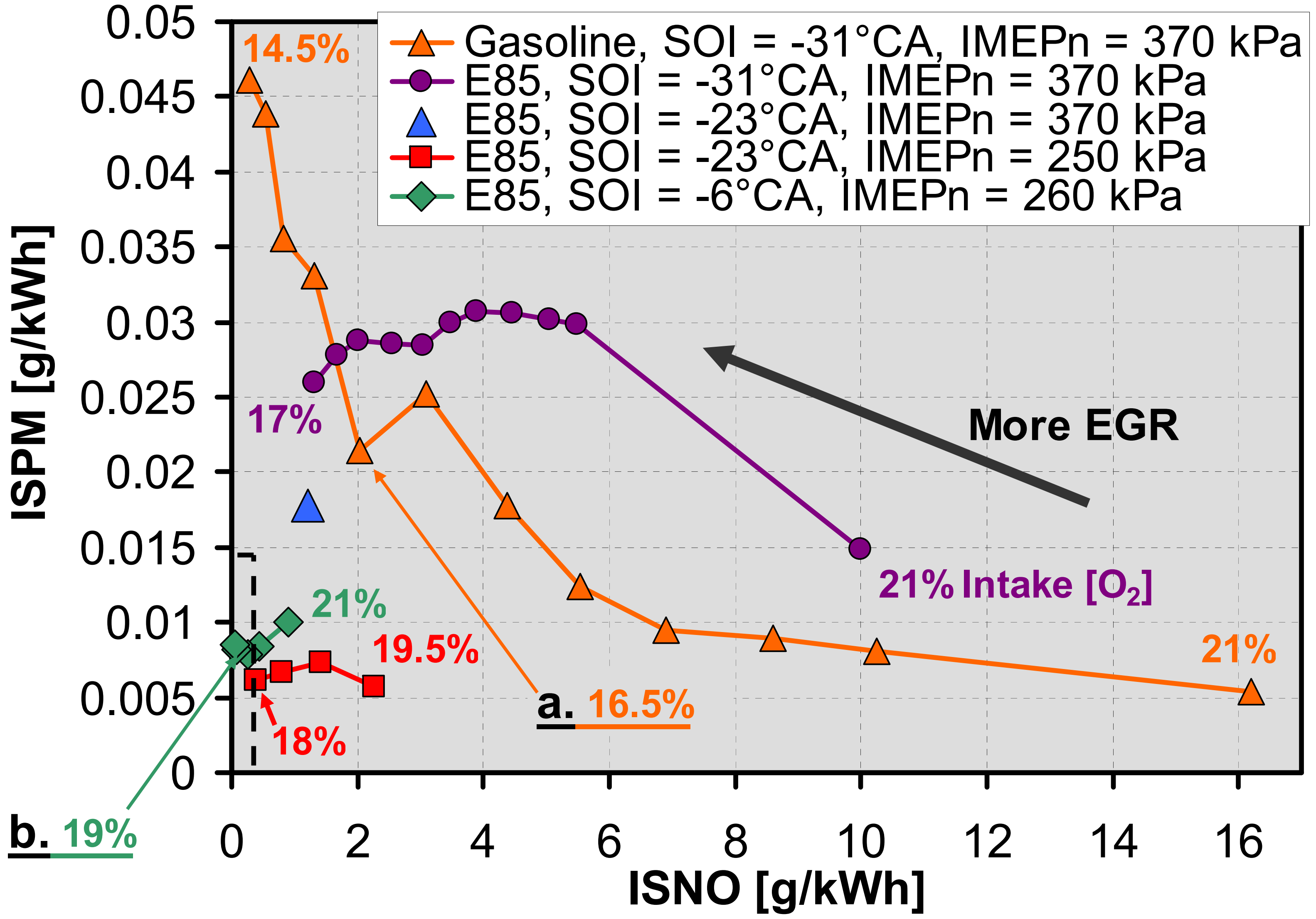


- Overcome this with fuel stratification to raise local ϕ.
- Allows lean and throttle-less engine operation.
  - High γ, and no pumping losses.
    $\Rightarrow$ High efficiency.
- Example for E70 fuel.
- Strongest gain of fuel economy for low loads.
  - 30% FE gain at ¼ load to 60% near idle.
- Overall 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.

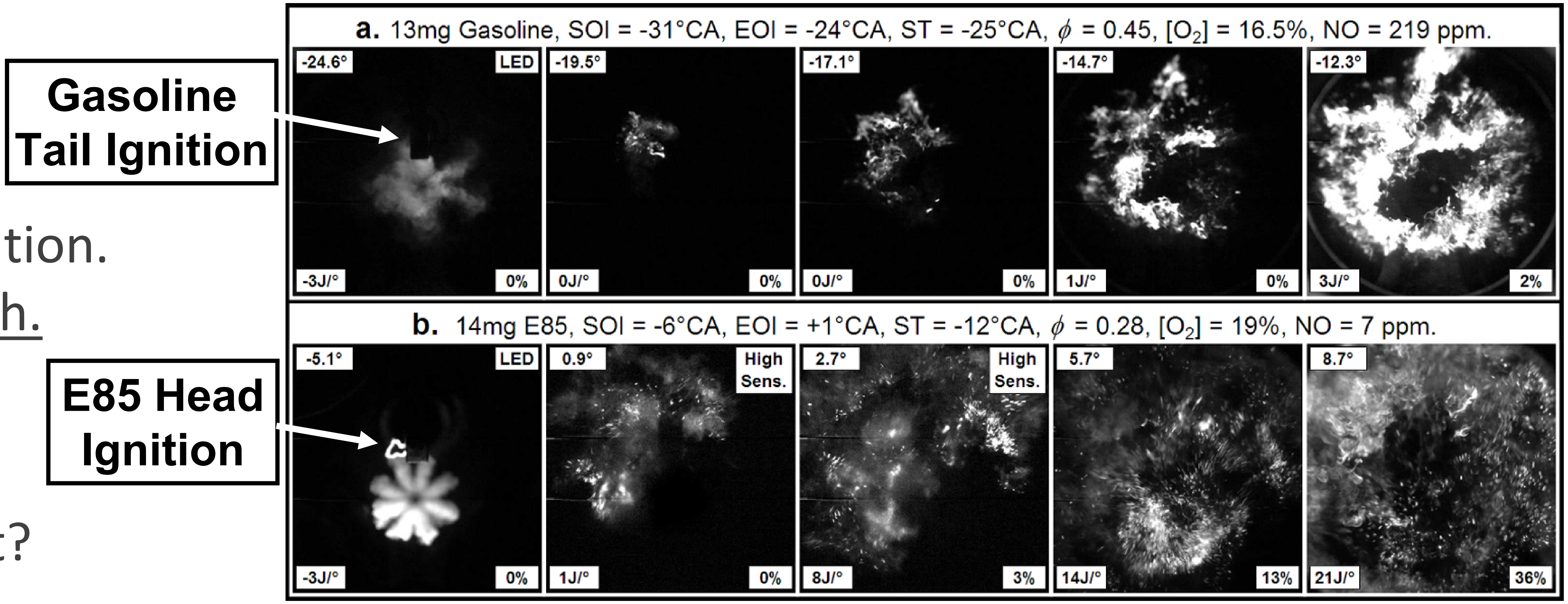


Previous Results - Reaching Inside NO/PM Box

- With E85, can reach inside the US2010 NO/PM box, using near-TDC injection.
- 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.

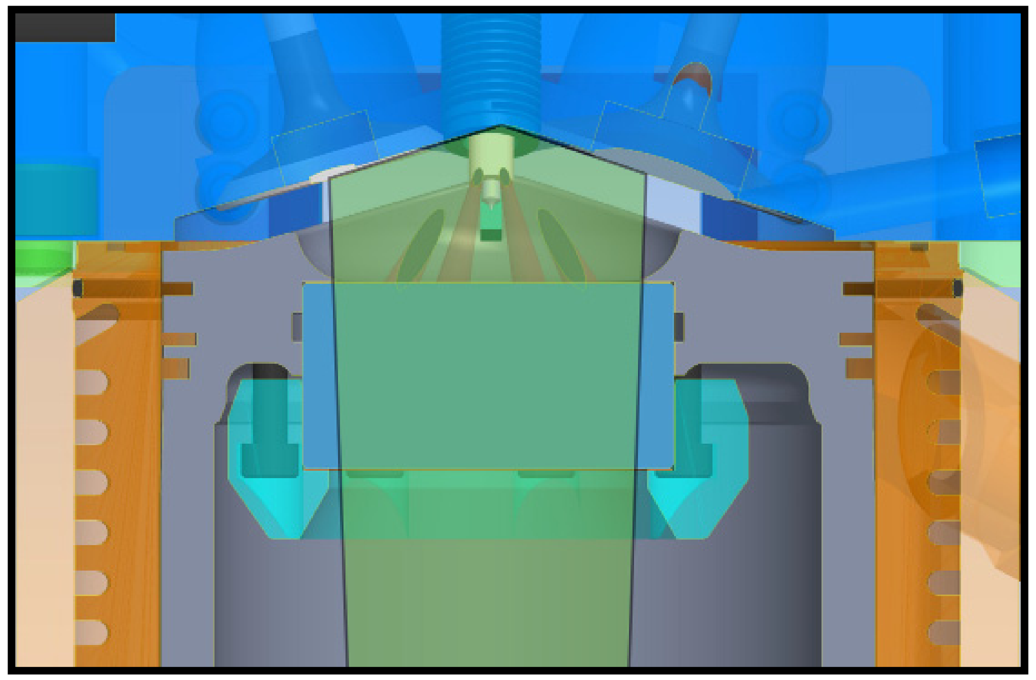


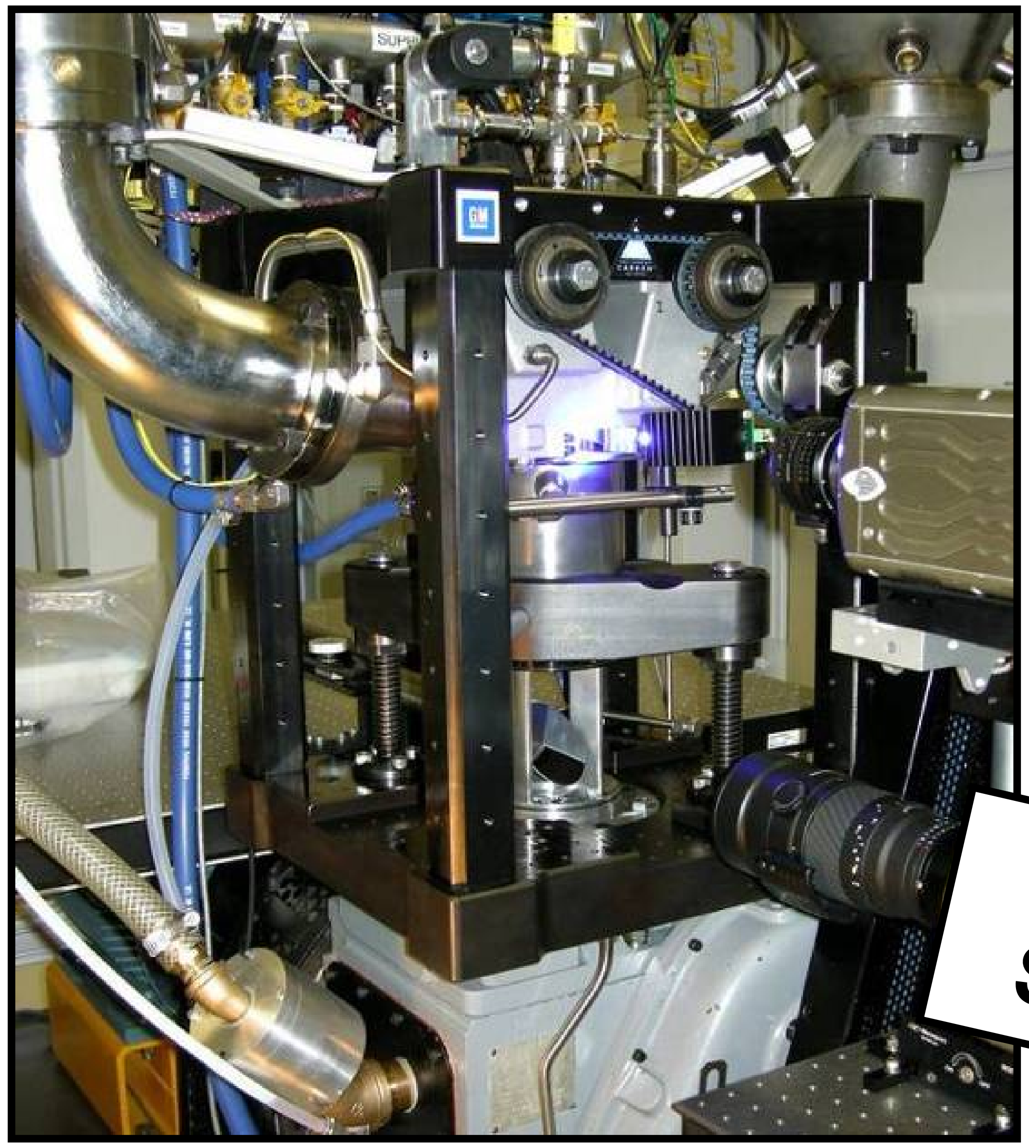
- Less flame-like combustion for E85 warrants further investigation.
- Use spectrograph.
- Nature of early faint flames?
- Presence of soot?

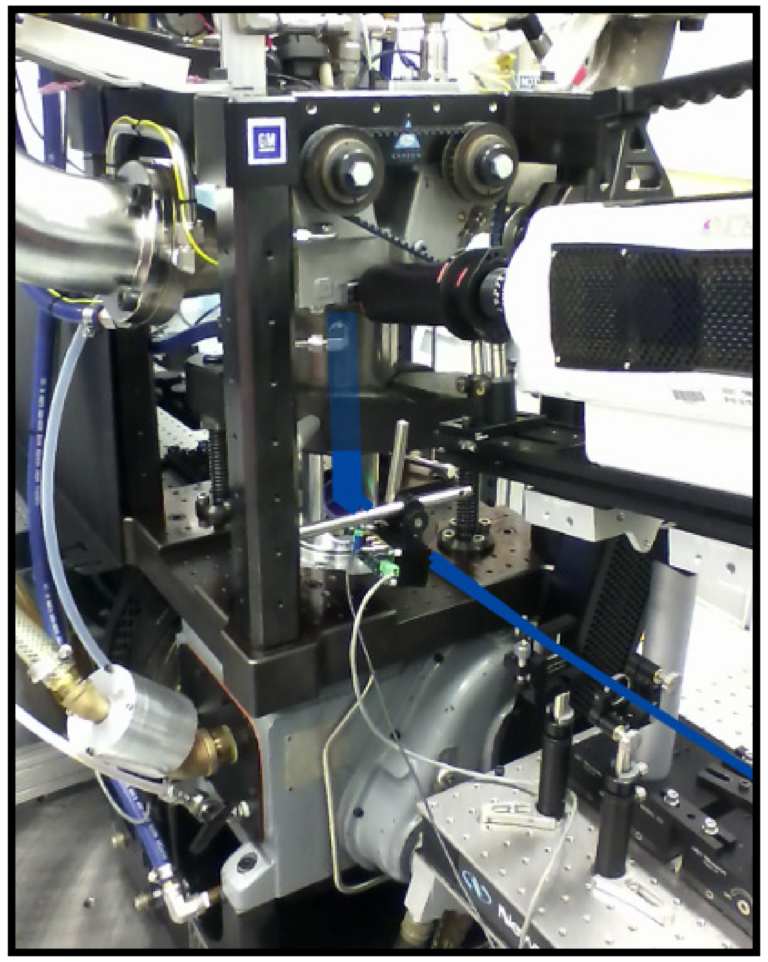


Optical Diagnostics Setups

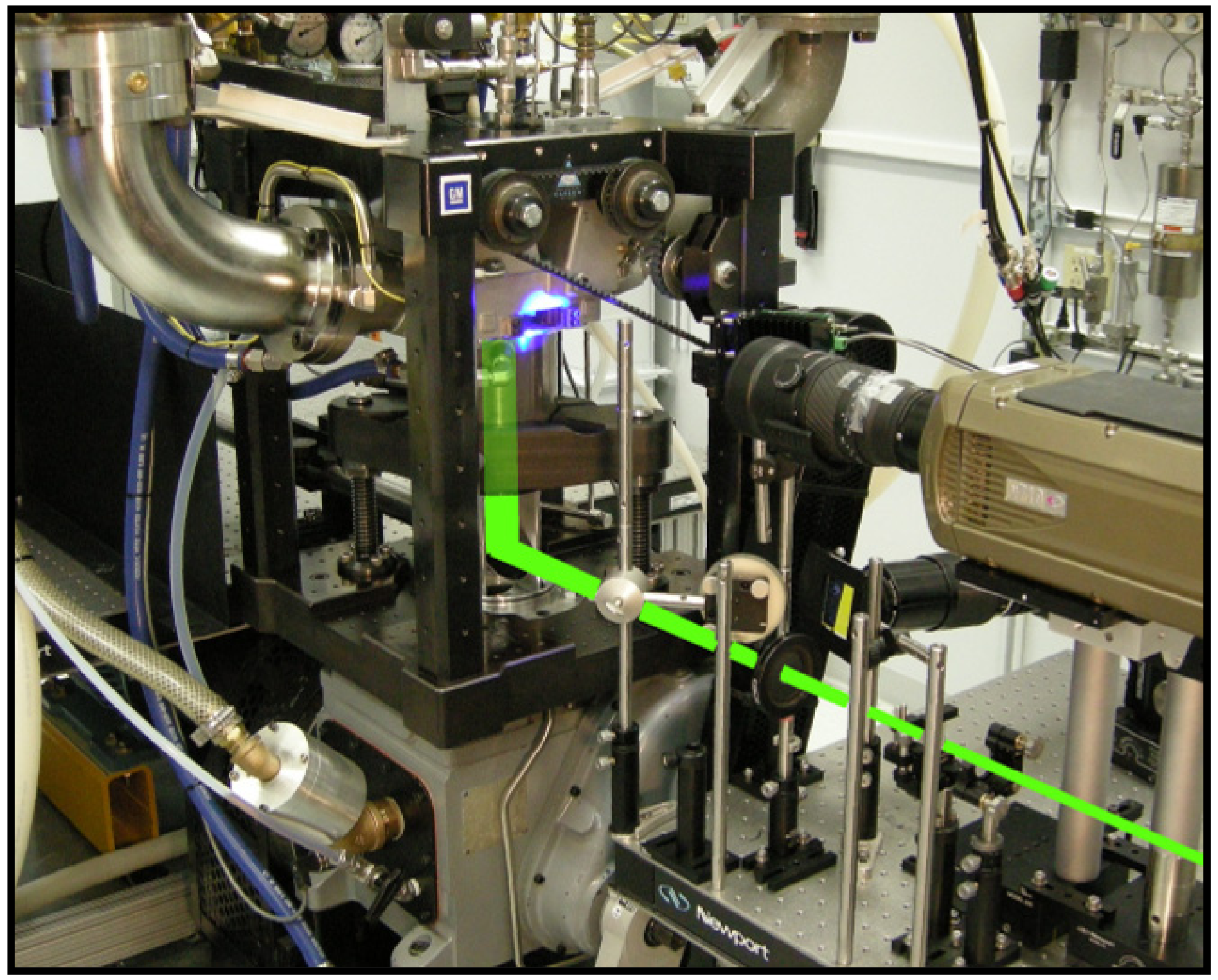
- PLIF high-speed 355 nm laser – Quantronix HP-UV. Intensified Phantom v311.
- In-house developed pulsed high-intensity LED for Mie-scattering.
- PIV high-speed 532 nm laser - Quantronix Dual Hawk.
  - Vertical laser sheet near spark-plug gap.
- Mie & natural luminosity imaging via Bowditch mirror.
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





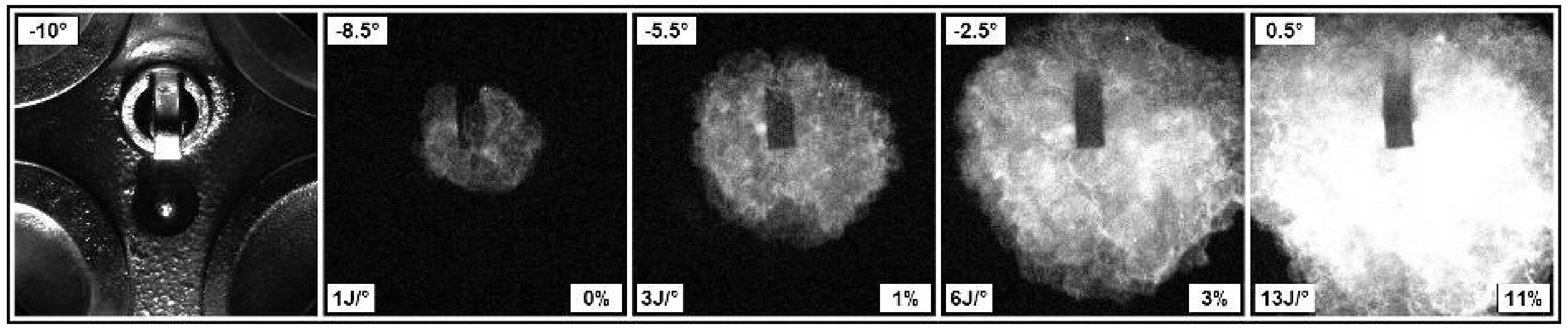


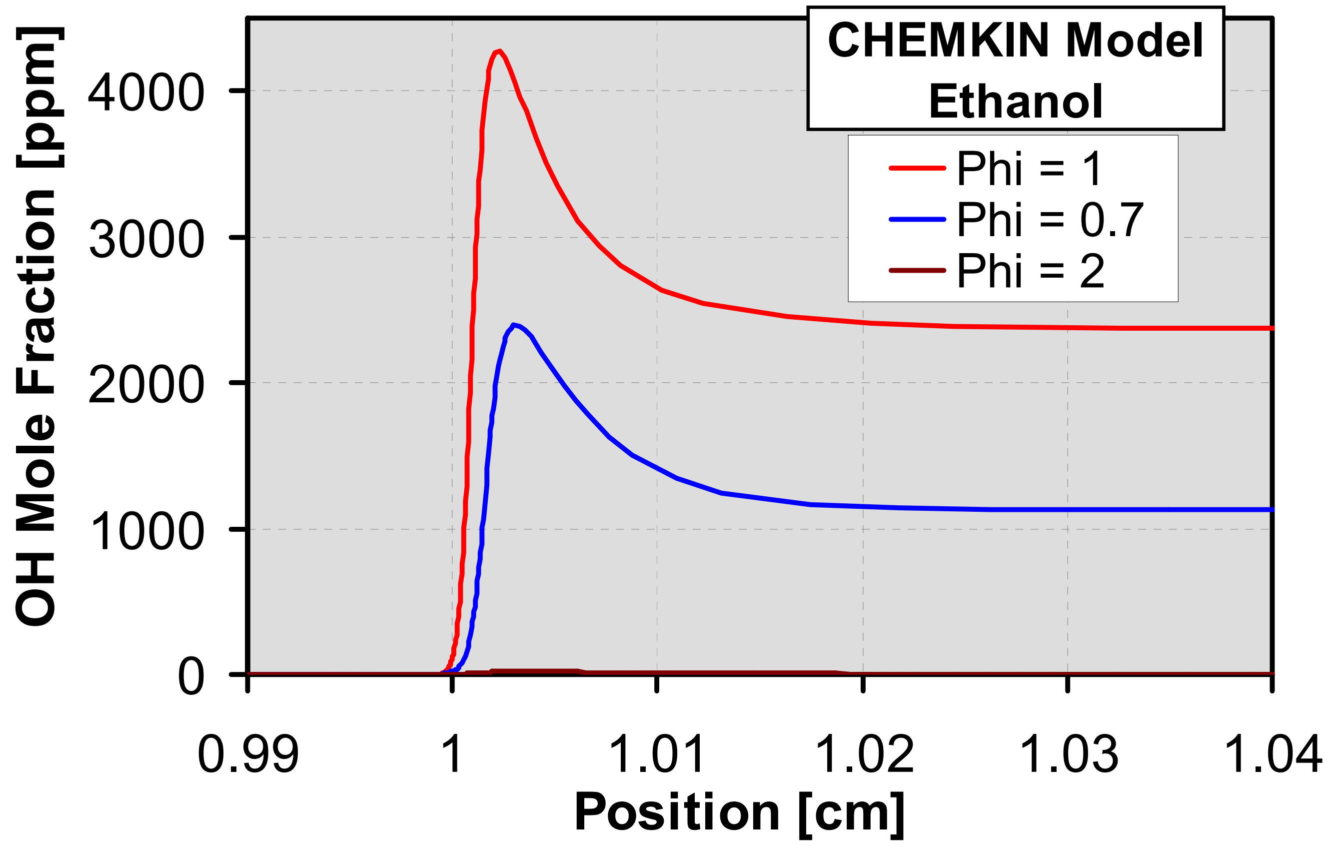
v7.10 or Spectrograph

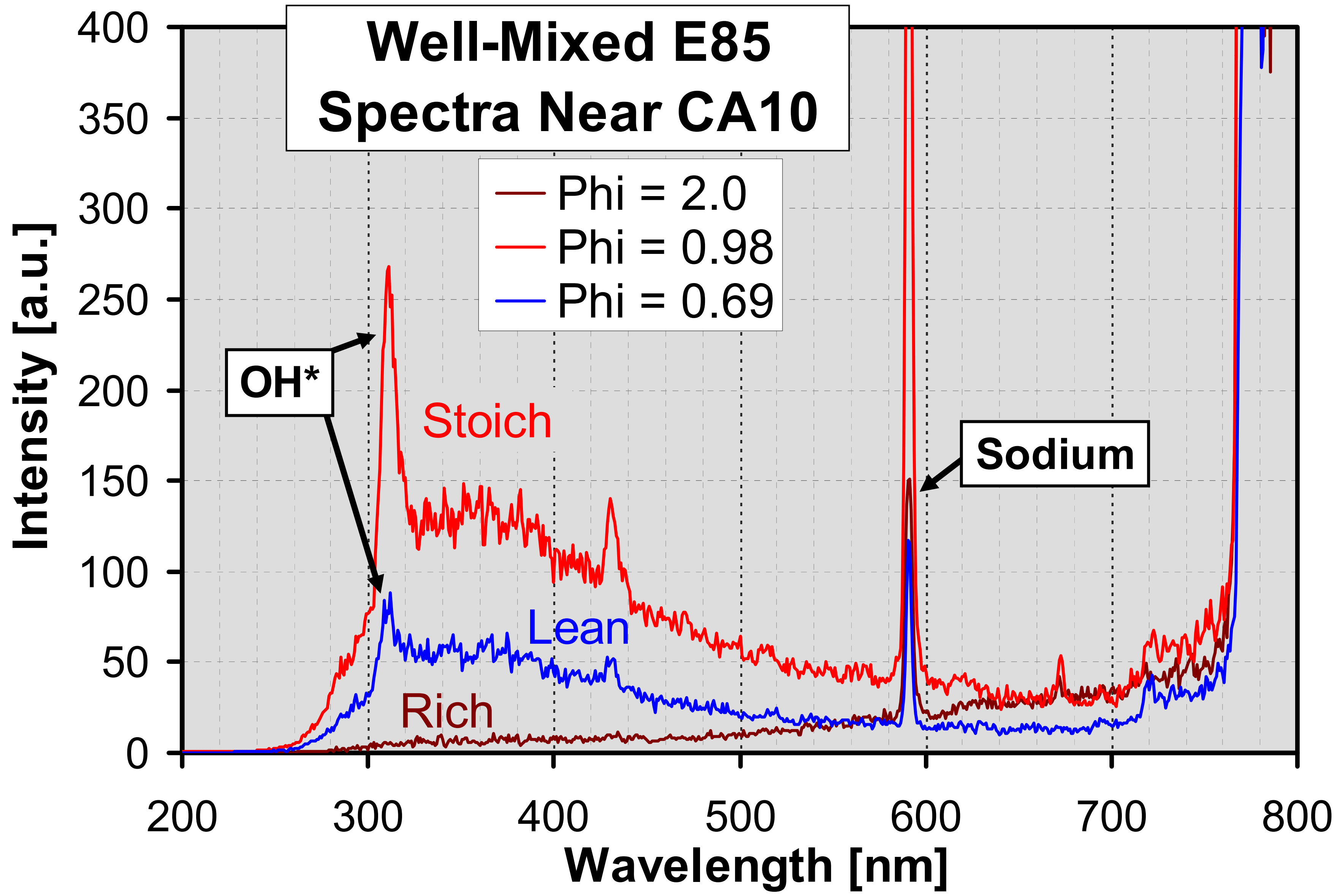


Well-mixed Spectral Response

- 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.

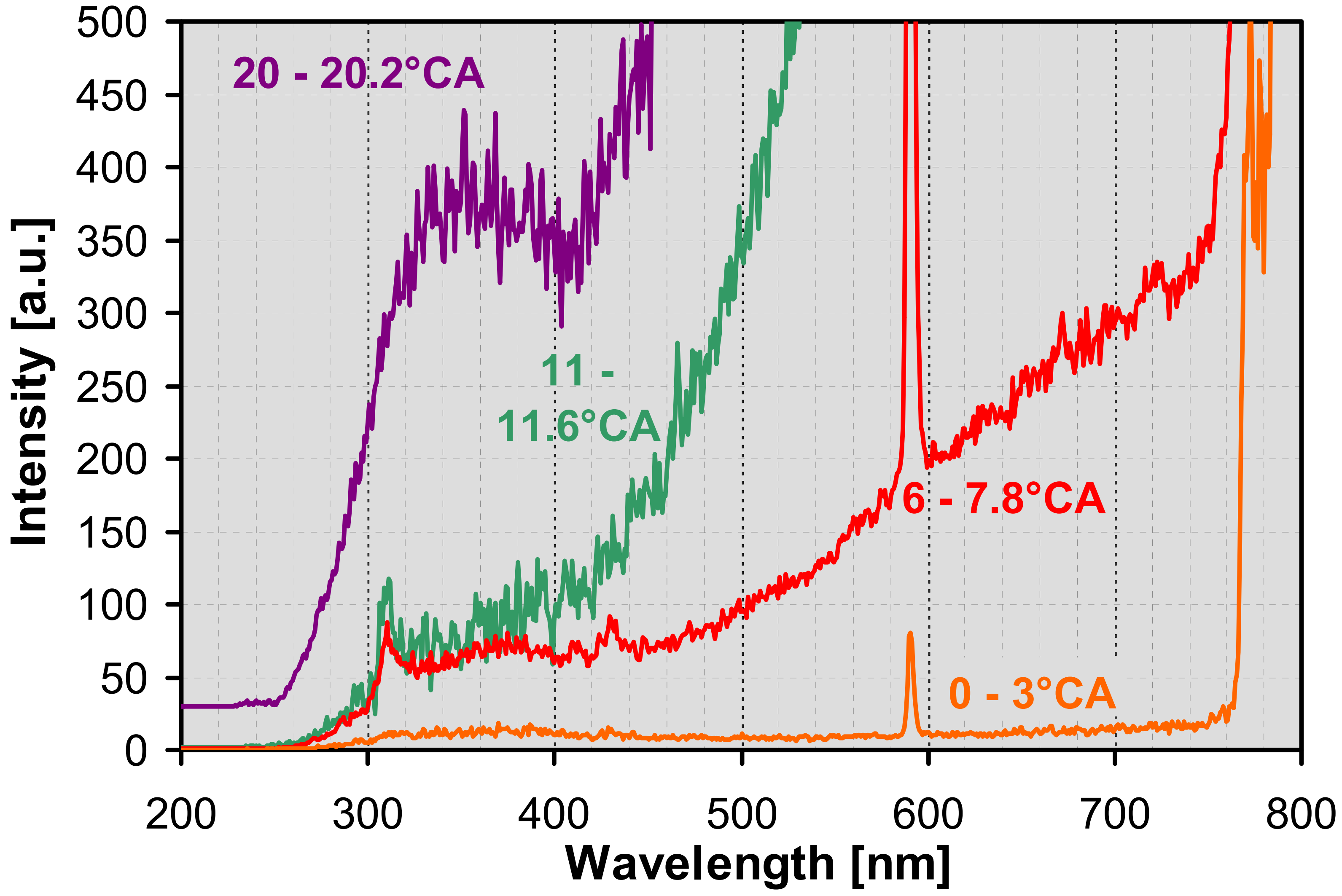


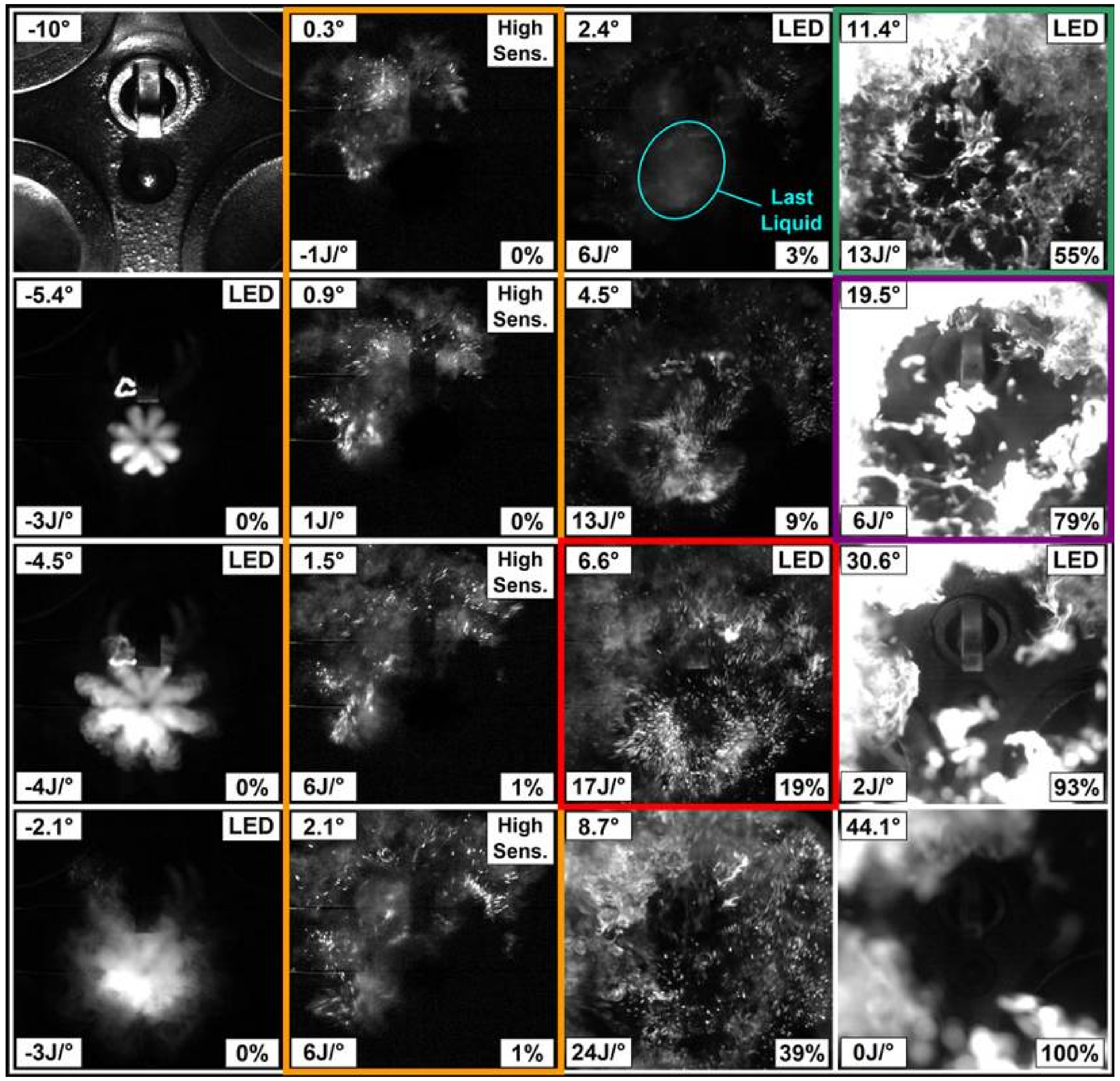


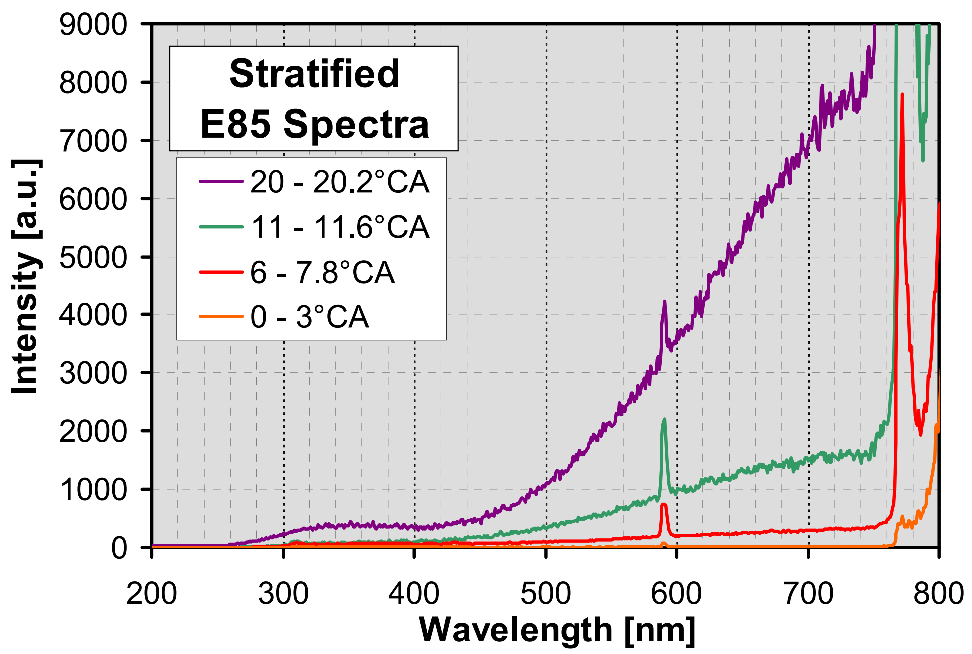


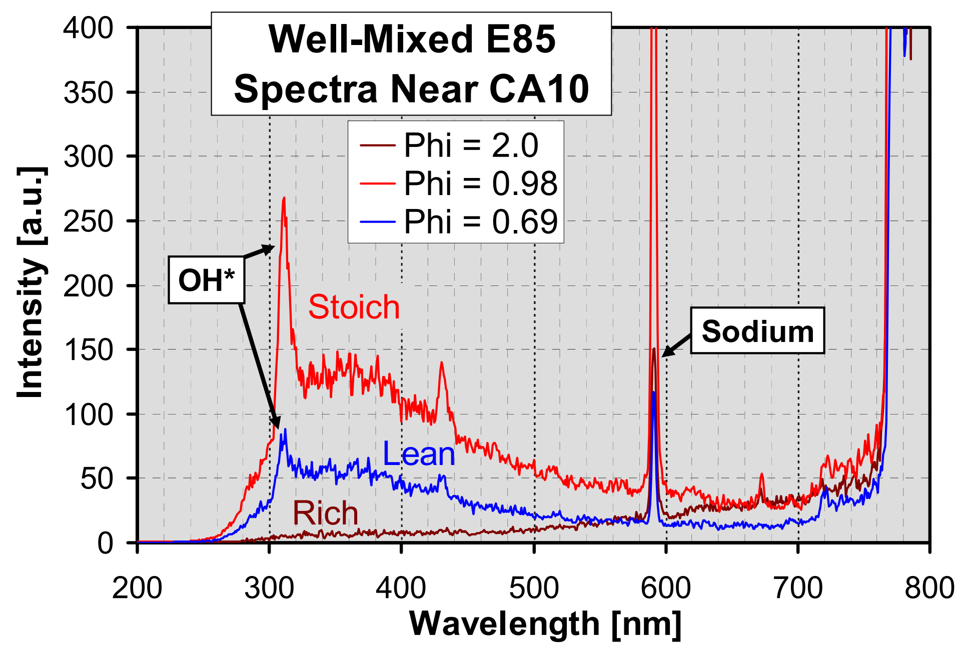
Stratified Spectra

- 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.



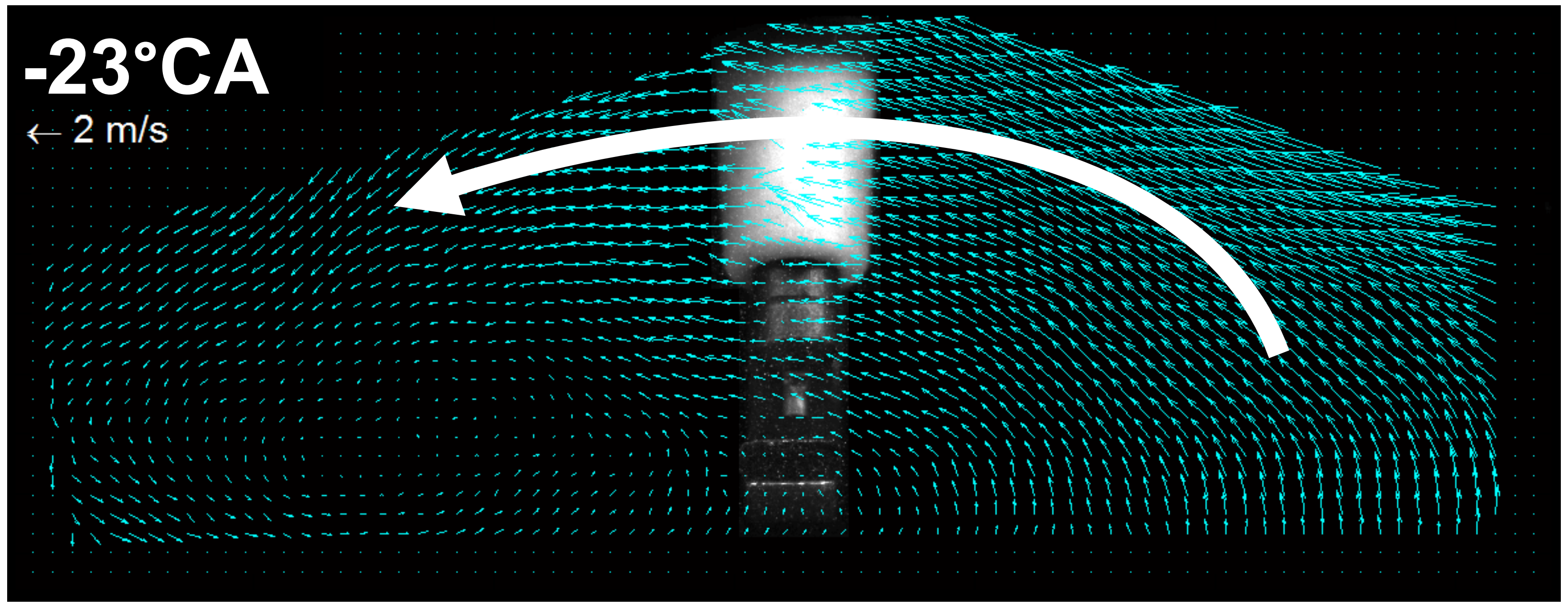


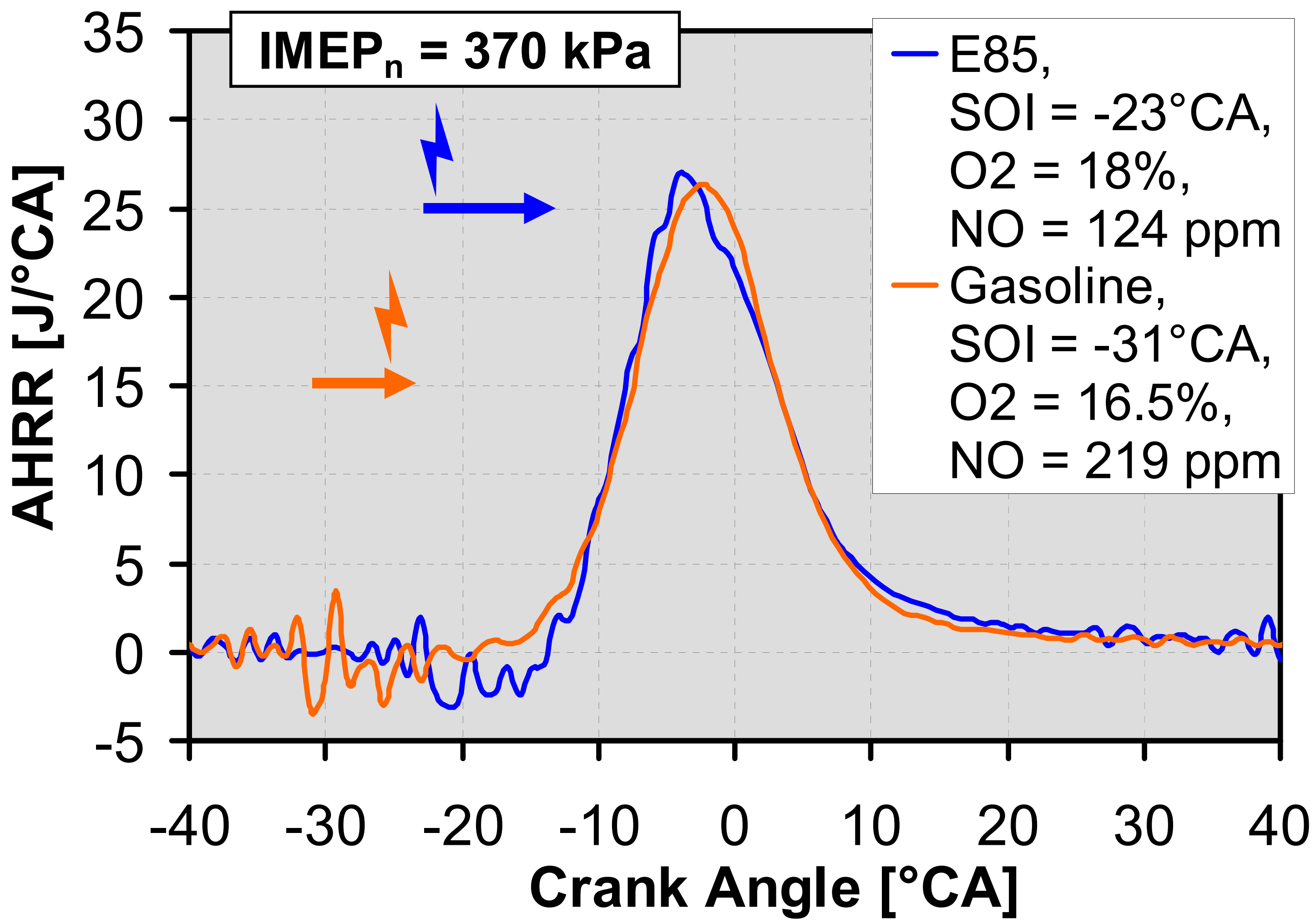




NO Emissions for Gasoline and E85

- 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.

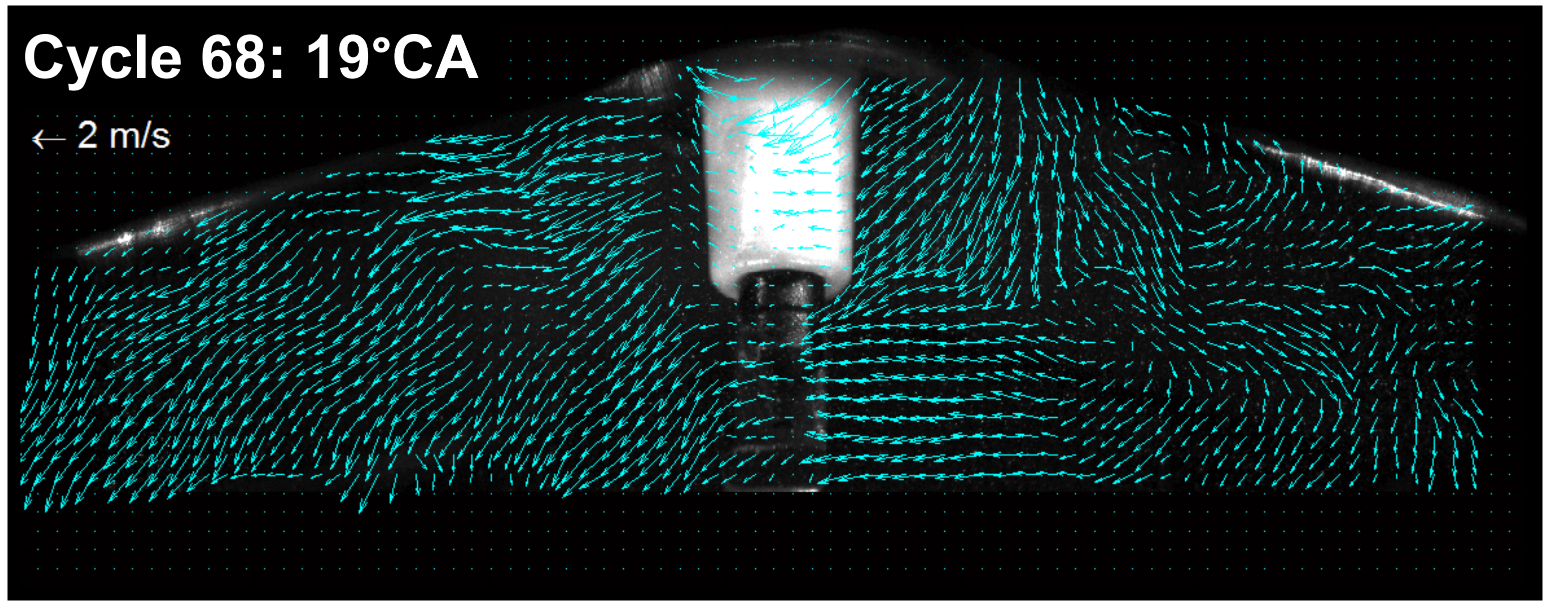




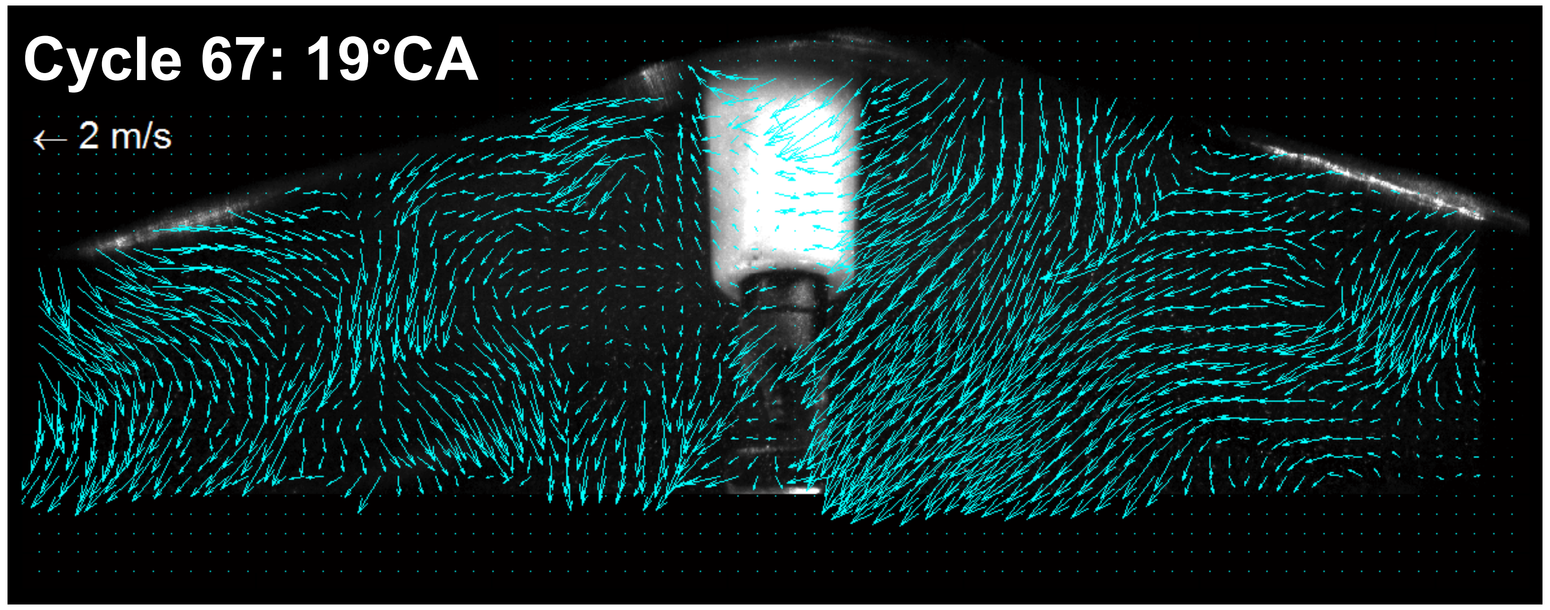
Mixing Rates Vs. NO Emissions

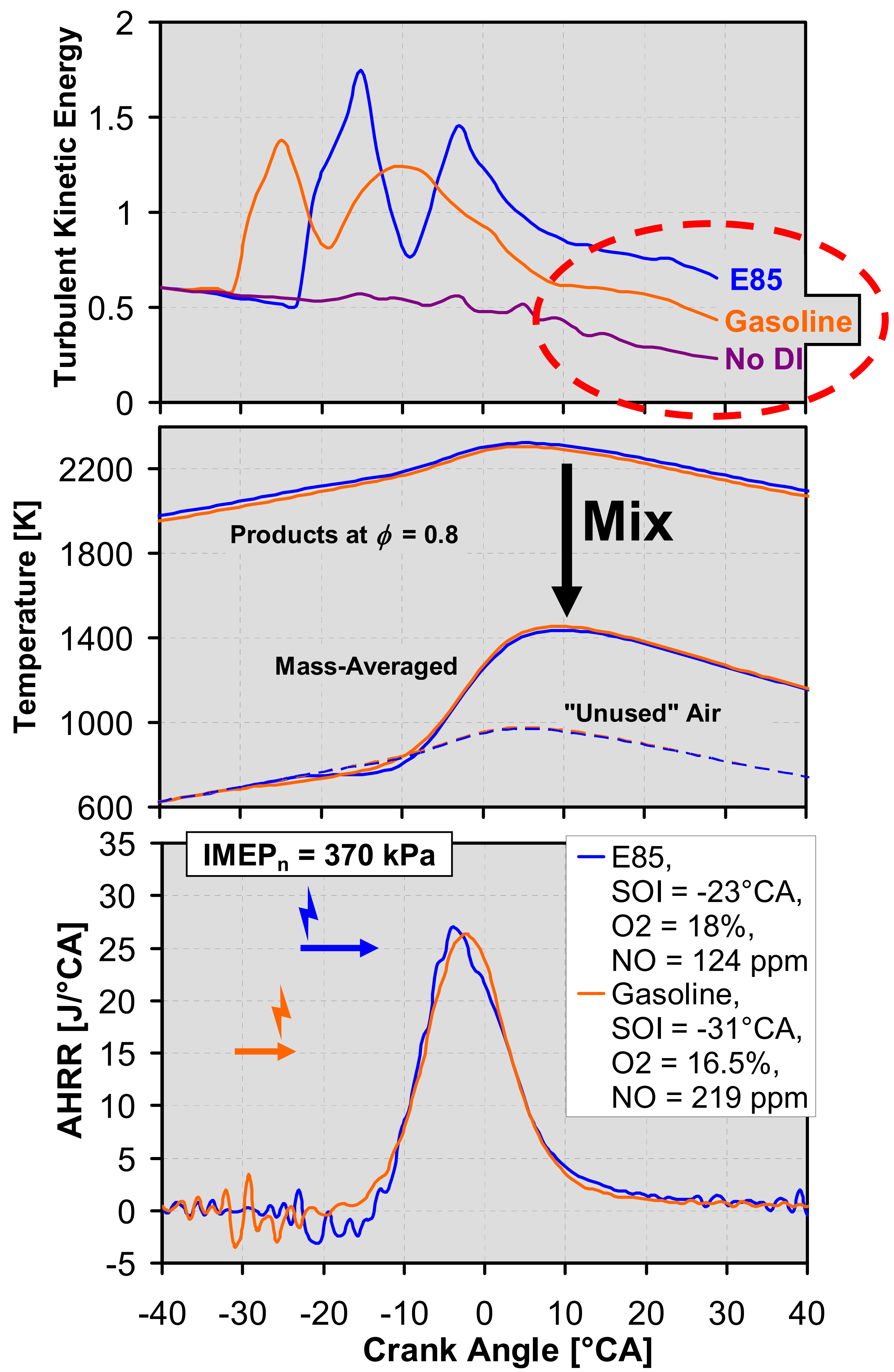
- PIV shows that in-cylinder turbulent kinetic energy is higher during burn-out for E85.
  - Lower heating value of E85 ⇒ 52% more fuel injected ⇒ More fuel-jet momentum.
  - More closely-coupled injection and combustion.

Gasoline



E85





- 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

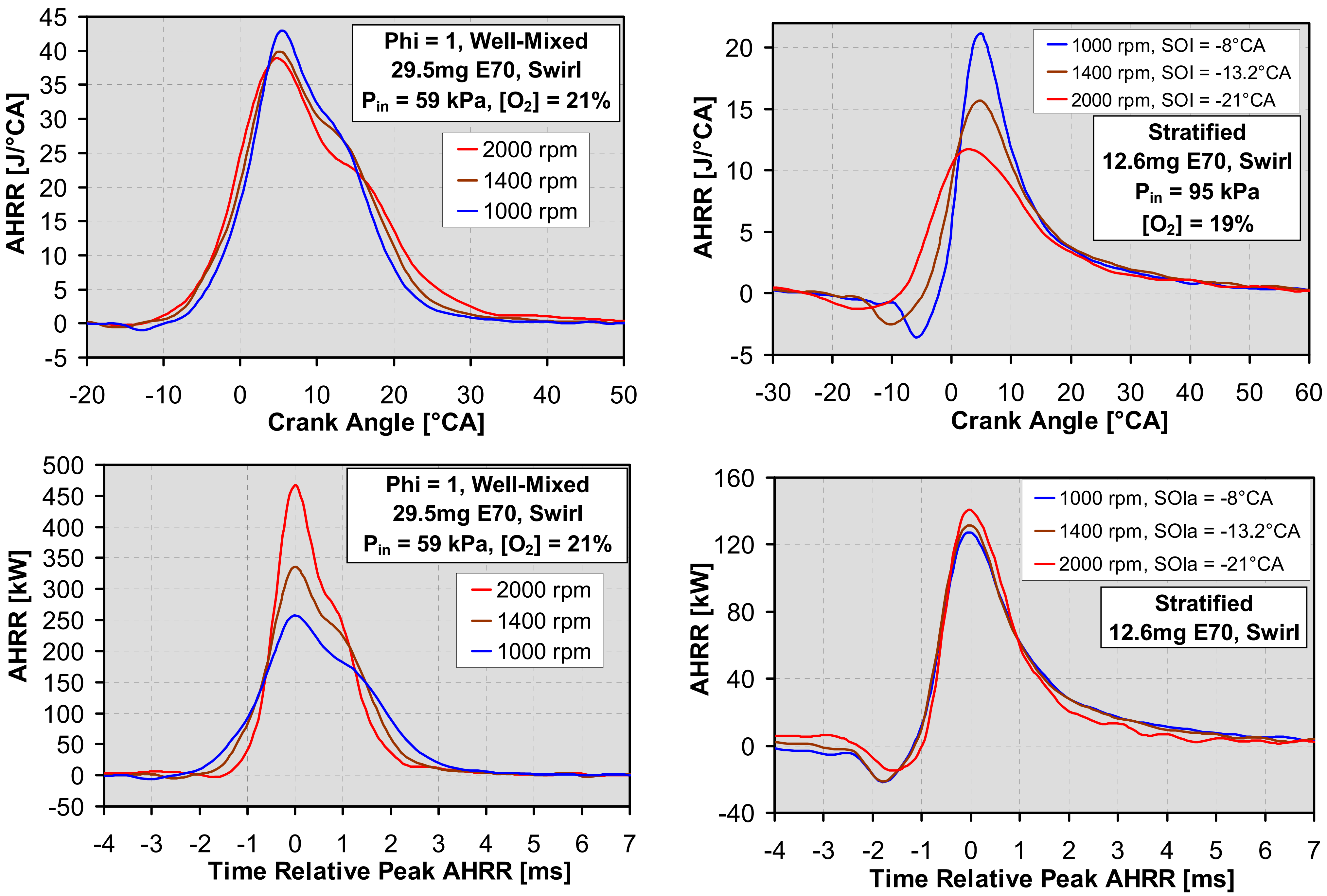
What is the role of the in-cylinder flow field for stratified-charge combustion?

– 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.

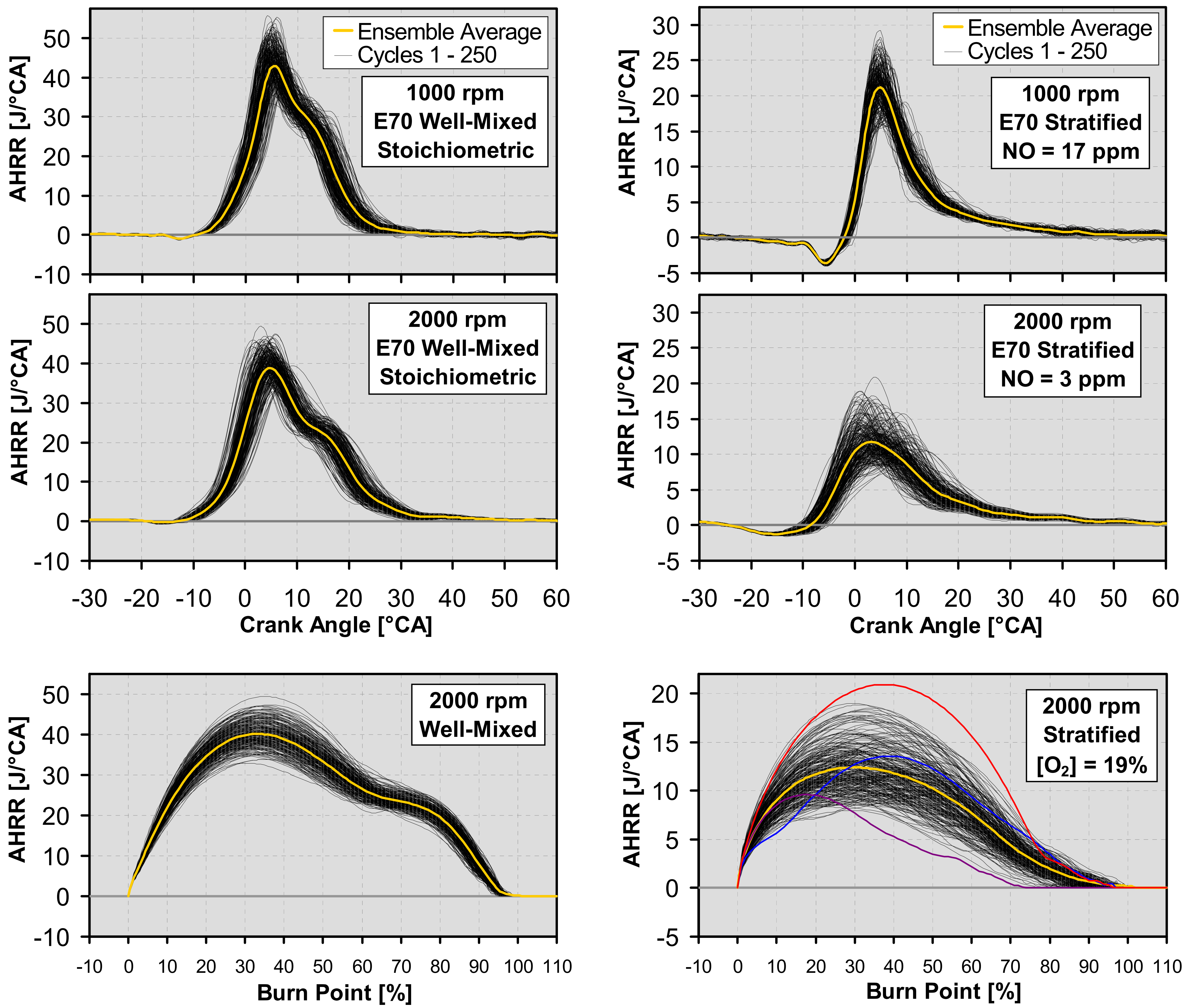
- Stratified combustion rate constant in kW/ms.
- Combustion rate governed by fuel/air mixing.
- On average, this mixing is dominated by fuel-jet penetration.

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



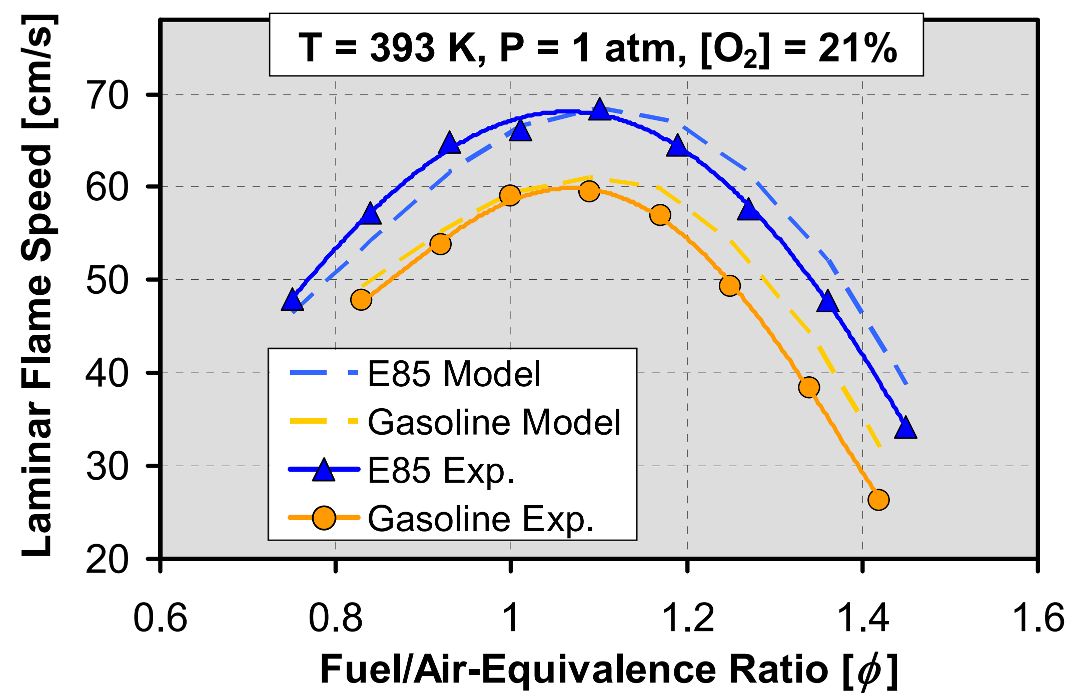
In-Cylinder Flow Field vs. Cyclic Variability

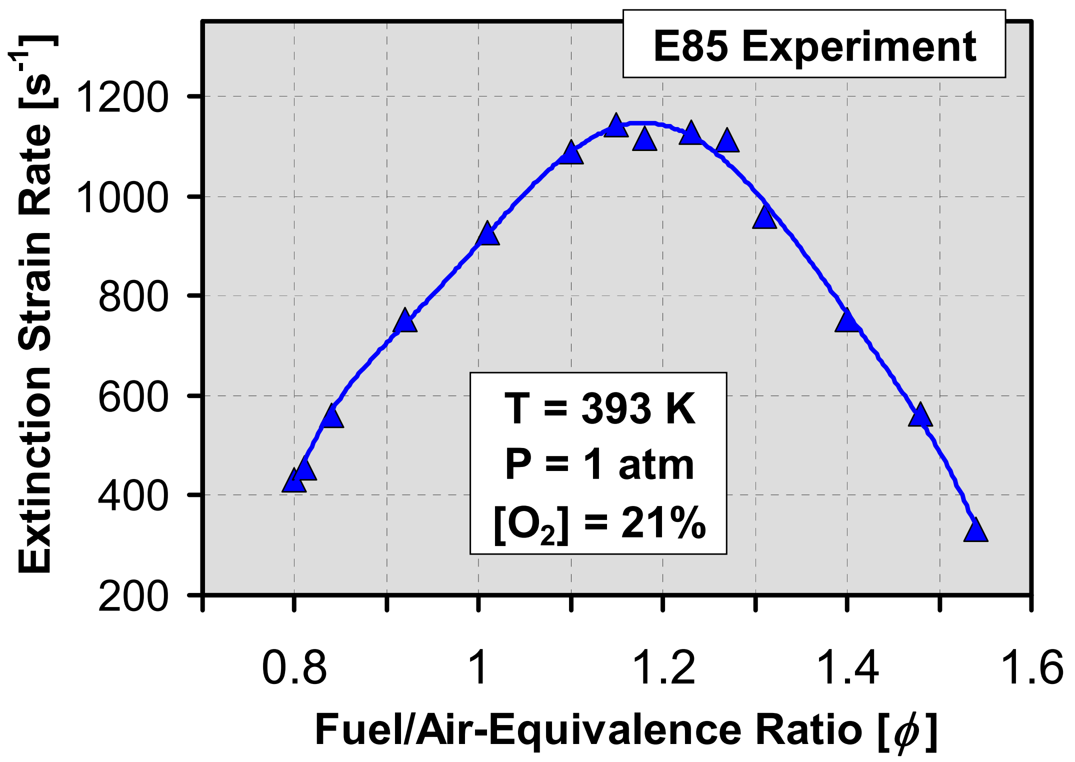
- Well-mixed operation: Relative cyclic variability does not change.
- Stratified combustion: rpm ⇑, in-cylinder flow field becomes sufficiently strong relative to the fuel jets ⇒ increased variability of combustion.
- CA50 variations make interpretation more difficult.
- Replot AHRR against % burn.
- 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.

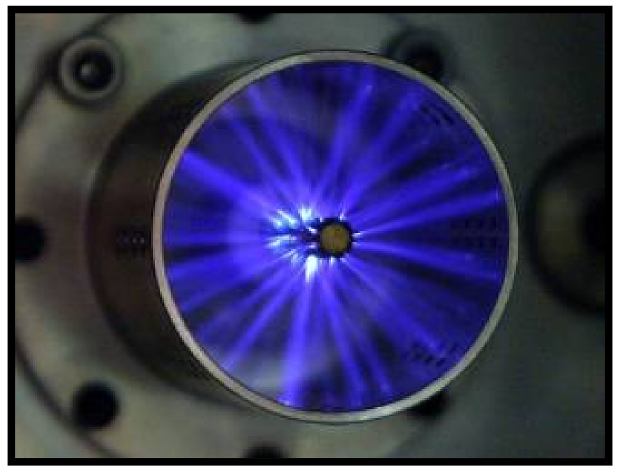


Collaborations / Coordination

- 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.



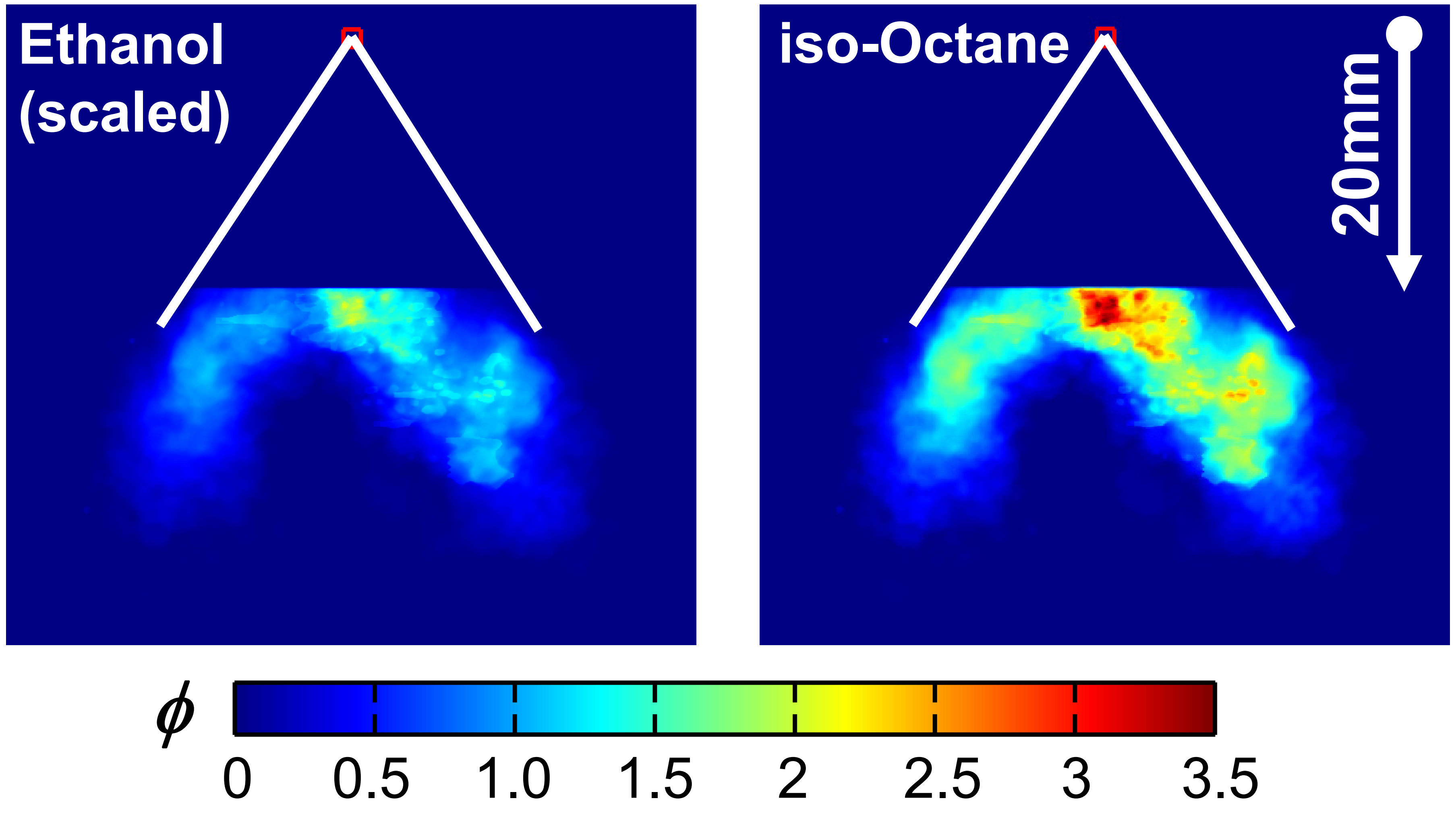




Collaborations (2)

Sandia Spray Combustion (L. Pickett)

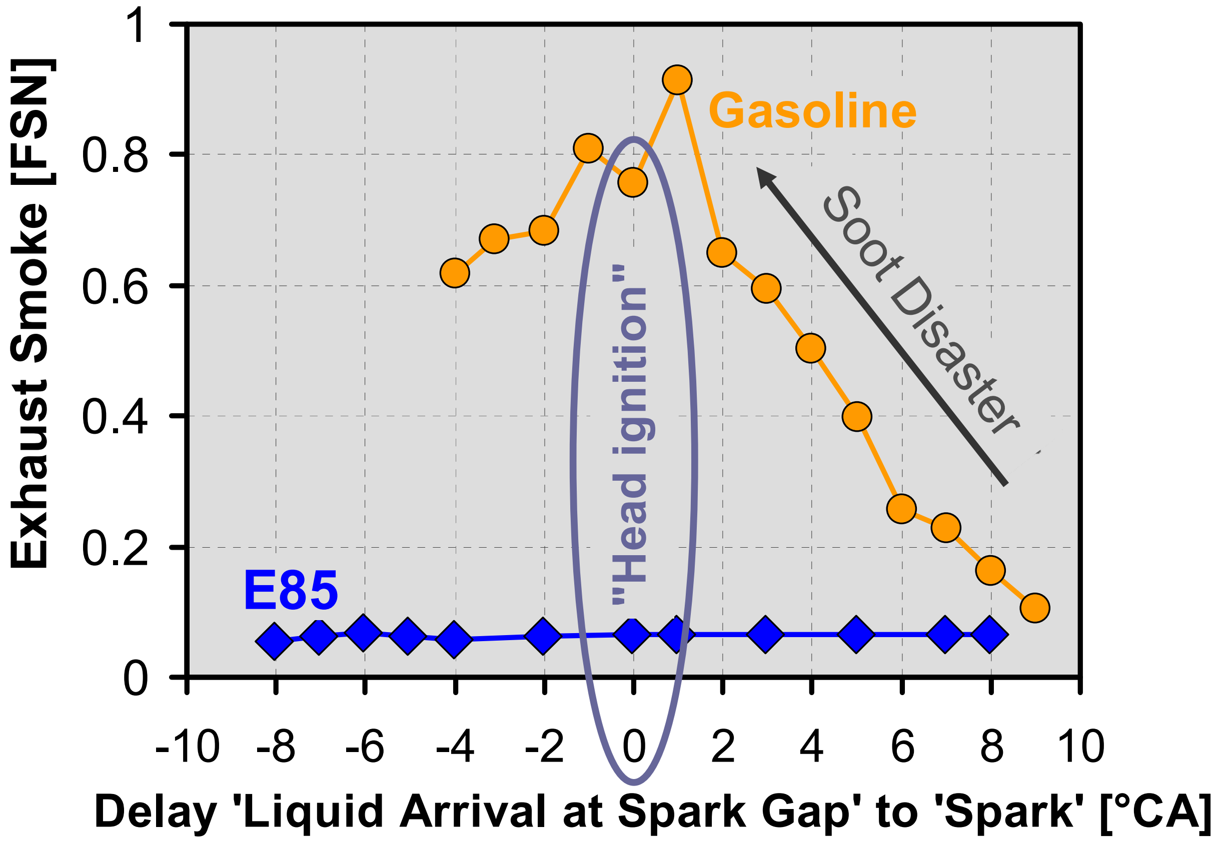
- Fuel effects on multi-hole sprays.
- Rayleigh-based measurement of fuel vapor for iso-octane.
  - Schlieren measurements indicate that air entrainment is very similar for ethanol.



- 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.