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Characterization of Spray-guided DISI Engine Combustion with near-TDC Injection of E85 using High-Speed Imaging, Spectroscopy, Flame Measurements and Modeling

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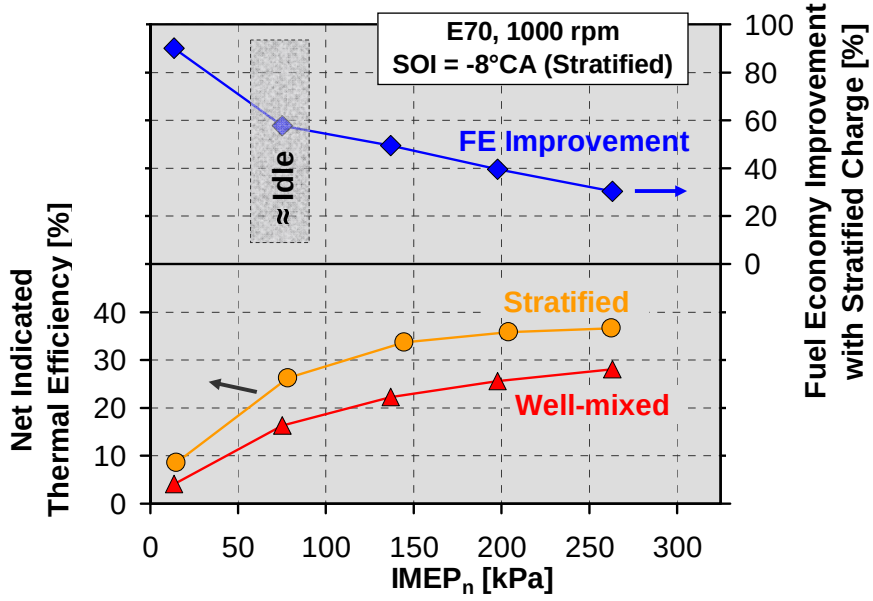
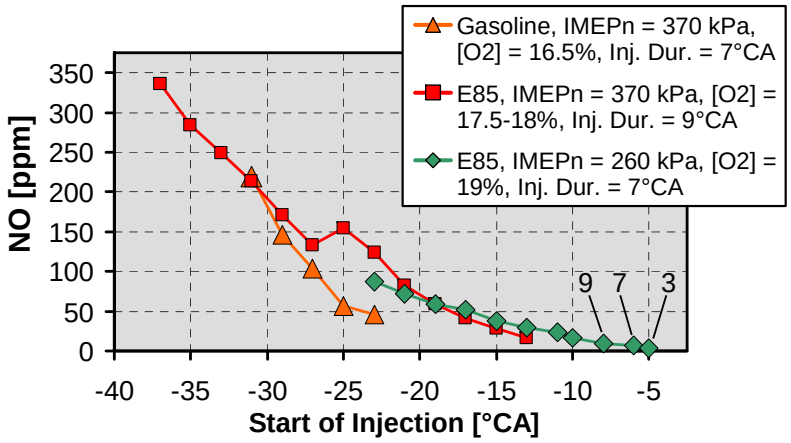
Introduction

- Overall lean but **stratified combustion** can improve fuel economy.
- High γ, and no pumping losses.
  $\Rightarrow$ High efficiency.
- 30% FE gain at ¼ load to 60% near idle.
- Overall lean operation prevents easy exhaust aftertreatment of NO_x.
- Ensure low engine-out NO_x and PM.
- High-ethanol blends and SOI retard are a beneficial combination.



Objective: Characterize the combustion mode with near-TDC injection of E85.

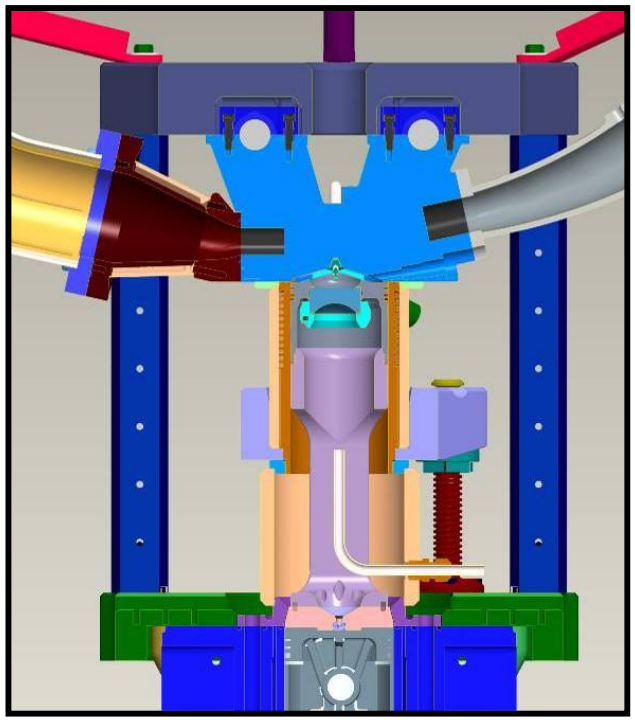
- Color and monochrome high-speed imaging.
- Spectroscopic work.
- Measurements of flame speed and extinction.
- Flame modeling in CHEMKIN.

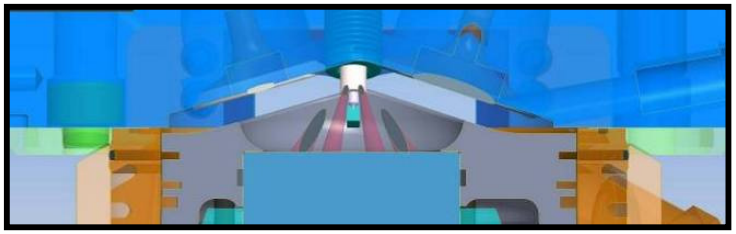


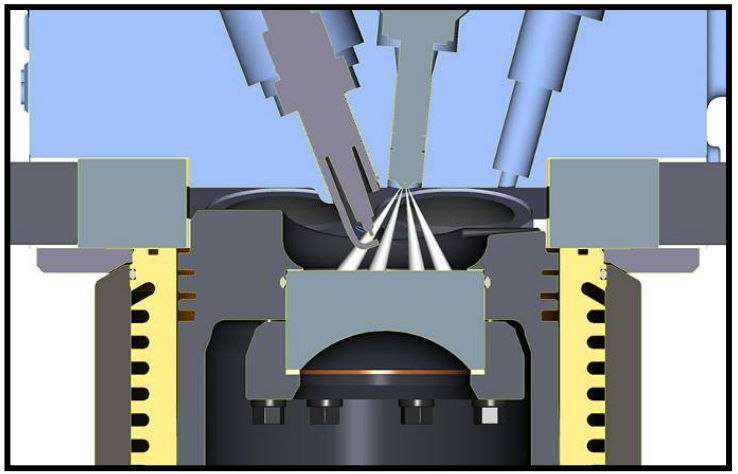
Research Engine

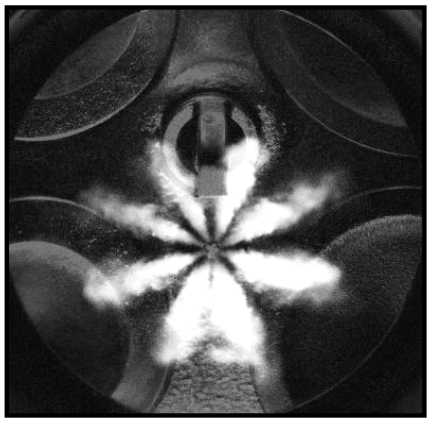
Two configurations of drop-down single-cylinder engine.
Bore = 86.0 mm, Stroke = 95.1 mm, 0.55 liter swept volume.

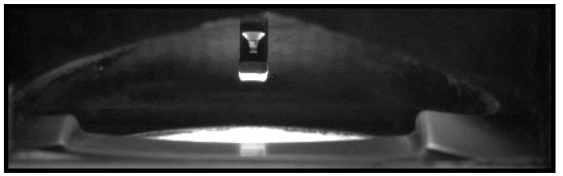
- All-metal: Metal-ring pack and air/oil-jet cooling of piston.
- Optical: Pent-roof window, piston-bowl window, and 45° Bowditch mirror.
- Identical geometry for both configurations, so minimal discrepancy between performance testing and optical tests.
- 8-hole injector with 60° included angle ⇒
  22°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











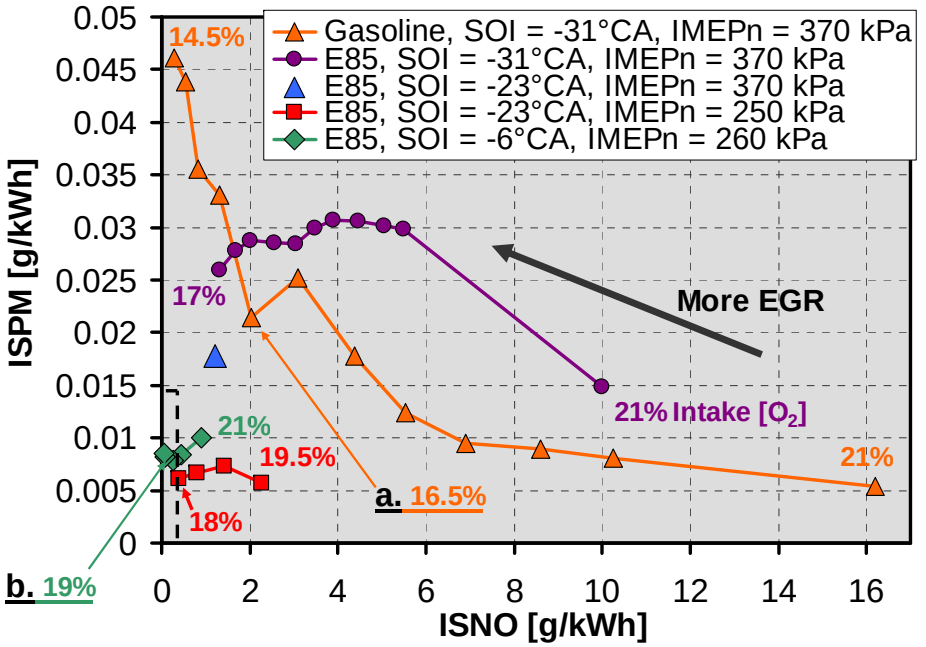
Reaching Inside NO/PM Box

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

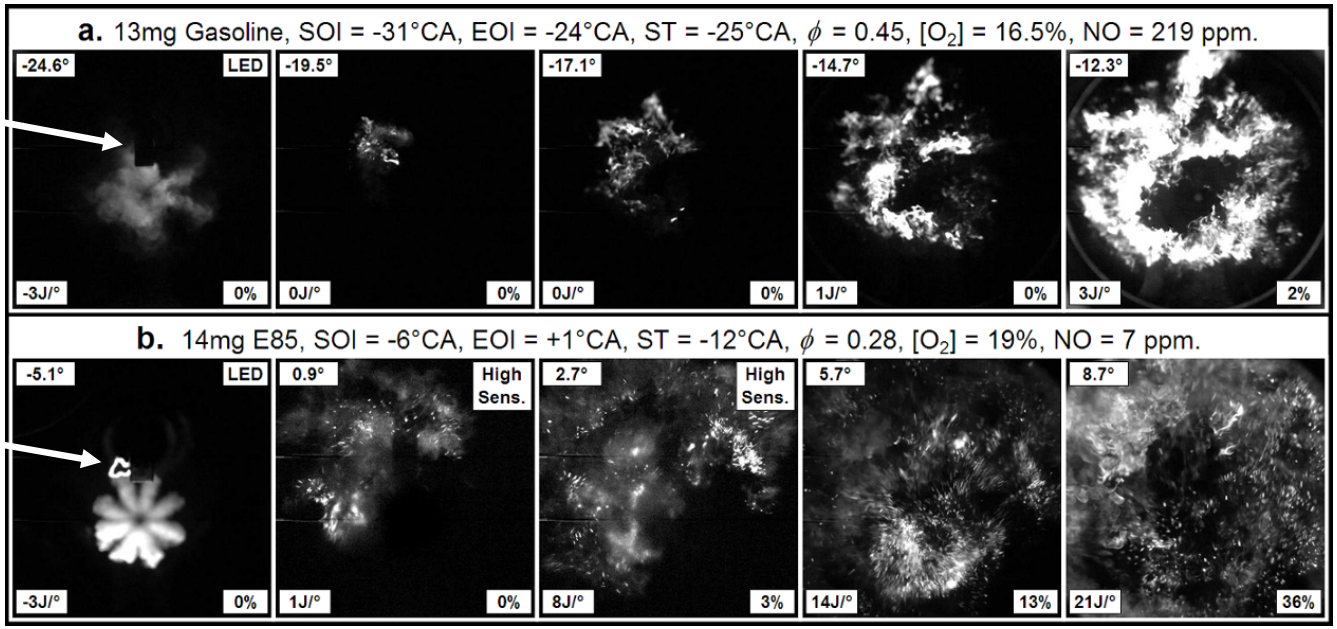
2012 Symposium on Combustion.

- E85 responds favorably to SOI retard.
  - Lower peak temperatures, and less residence time, ⇓ NO formation.

SAE 2012-01-1643.



Gasoline Tail Ignition



E85 Head Ignition

- Flame spread appears distinctly different for E85.
- Warrants further investigation.

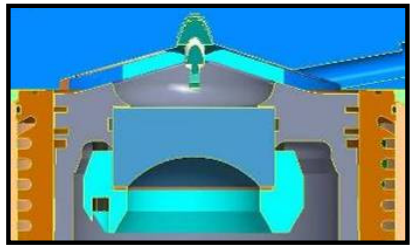
Parameter Space

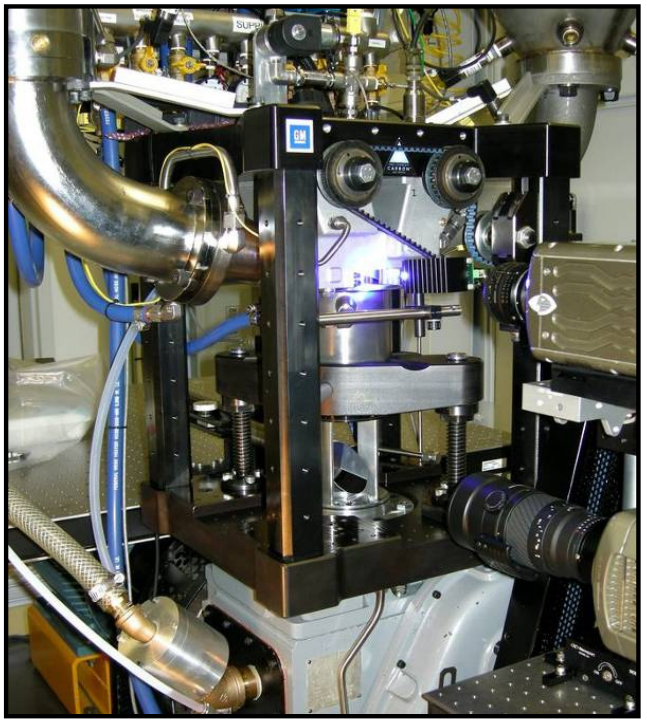
- The parameter space is huge.
- Grouped as hardware, static parameters & operating variables.
- Swirling in-cylinder flow.
- High spark energy.
- Acquired data for 500 cycles per steady-state operating point.
- Cylinder, intake, exhaust, & fuel pressure, and spark current.

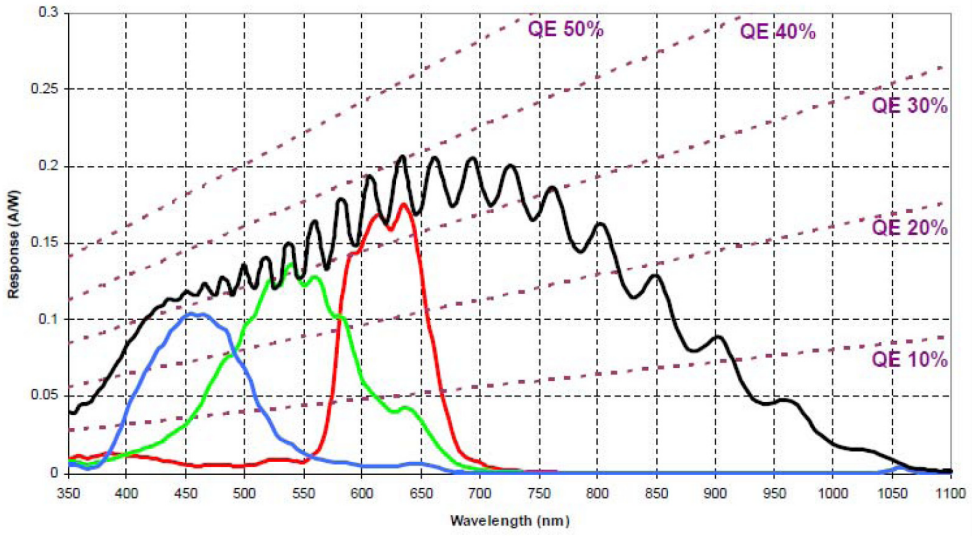
Parameter	Current Study
CR	12
Piston Bowl	Ø 46 mm
Swirl Index	2.7
Valve Timings	For Minimal Residual Level
Injector & Spray Targeting	Bosch 8 x 60° Straddling Spark
Injection Pressure	170 bar
# of Injections	Single
Spark Energy	106 mJ
$T_{coolant}$	60°C
T_{in}	26-28°C
Engine Speed	1000 rpm
Intake Pressure	95 kPa
$P_{exhaust}$	100 kPa
$IMEP_n$	260 kPa
Start of Injection (SOI)	-6°CA
Spark Timing (ST)	-12°CA
EGR / $[O_2]_{in}$	**19%** O_2 (or 18.5 -21)
Fuel Type	E85

Imaging Setup

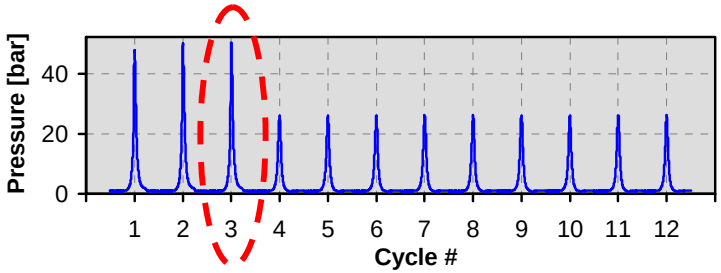
- Monochrome Phantom v710 or color Phantom v711.
- Wide-angle view via Bowditch mirror
- Monochrome CMOS chip ⇒ Broadband imaging.
  - Combine with band-pass filter.







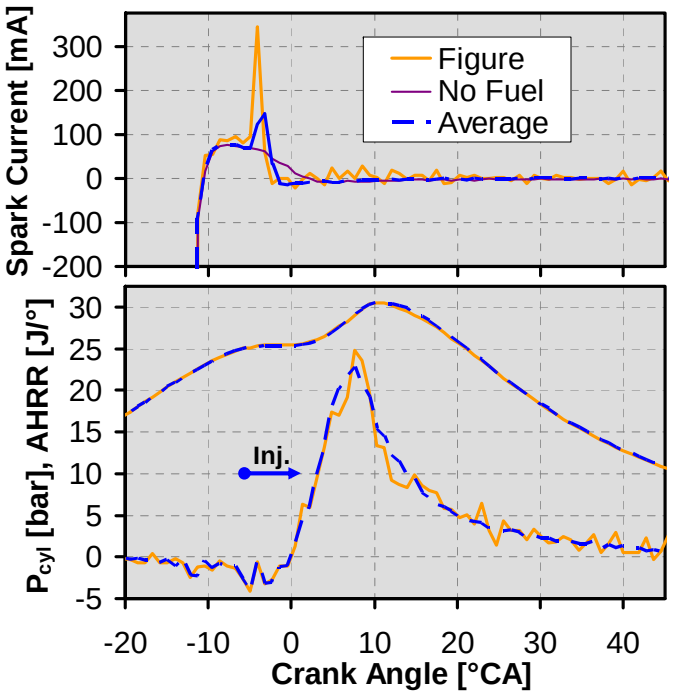
- Pulsed high-intensity LEDs for Mie-scattering.
  - 4µs (blue-green) or 5µs (blue) pulse length.
  - Skip-illumination for near-simultaneous Mie-scattering and flame imaging.
- 3/12 - skipfire operation for realistic residuals.



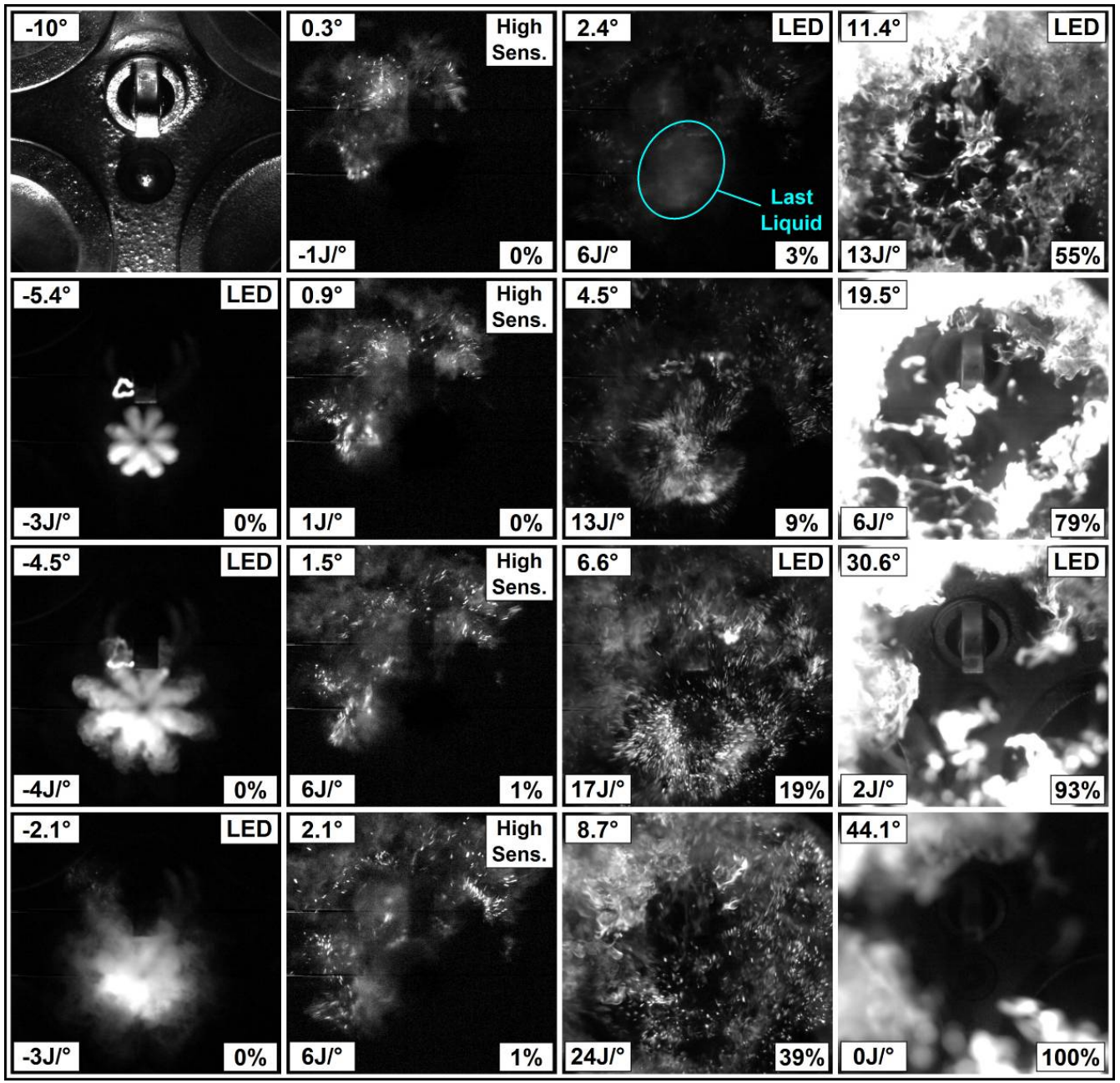
Monochrome High-Speed Imaging

- Statistically selected cycle.
- Combined Mie and natural luminosity.

- Closely coupled injection and ignition leads to highly turbulent combustion.



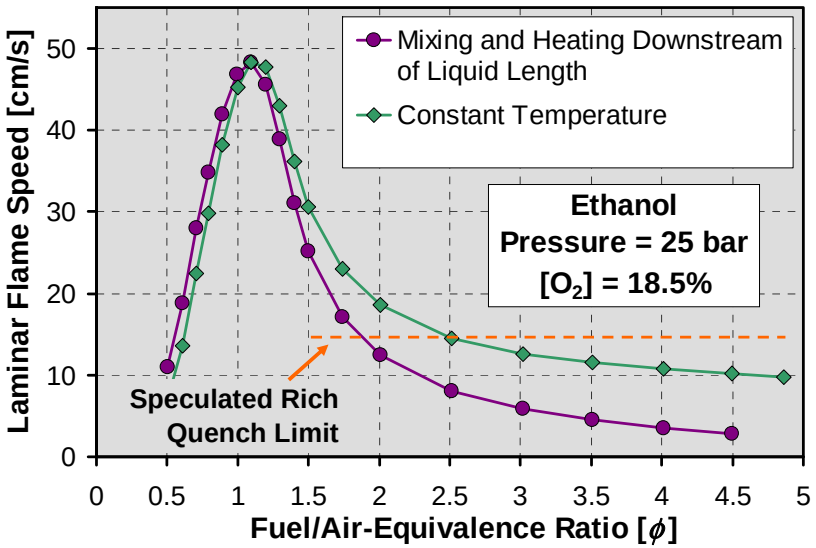
Spark = -12°CA, Intake [O_2] = 19%, Exhaust NO = 6 ppm

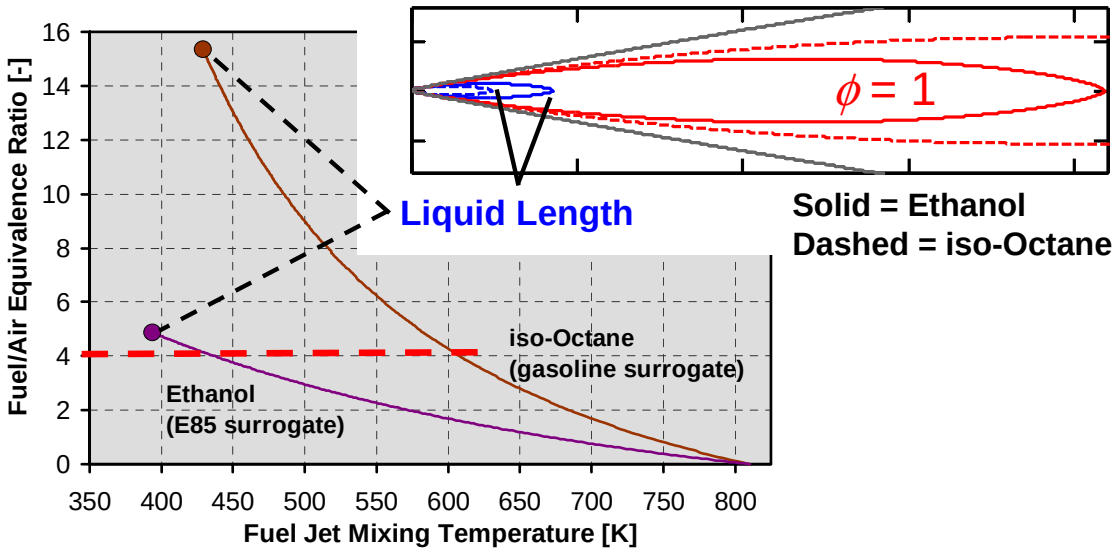


Fuel Vaporization / Flame Speed

- Why are exhaust soot levels so low, despite flame spread prior to fuel/air mixing?
- Ethanol in E85 makes fuel highly oxygenated.
- E85's large latent heat of vaporization:

1. Prevents very rich gas-phase mixtures.
   -- For ethanol $\phi_{max} \approx 5$, whereas $\phi_{max} \approx 15$ for iso-octane.
2. Makes richer zones much cooler.
   CHEMKIN predicts strongly suppressed flame speeds in these rich zones.
   -- Likely leads to low combustion activity in rich zones, suppresses soot formation.
   -- Examine light emissions from combustion to learn about presence of soot.

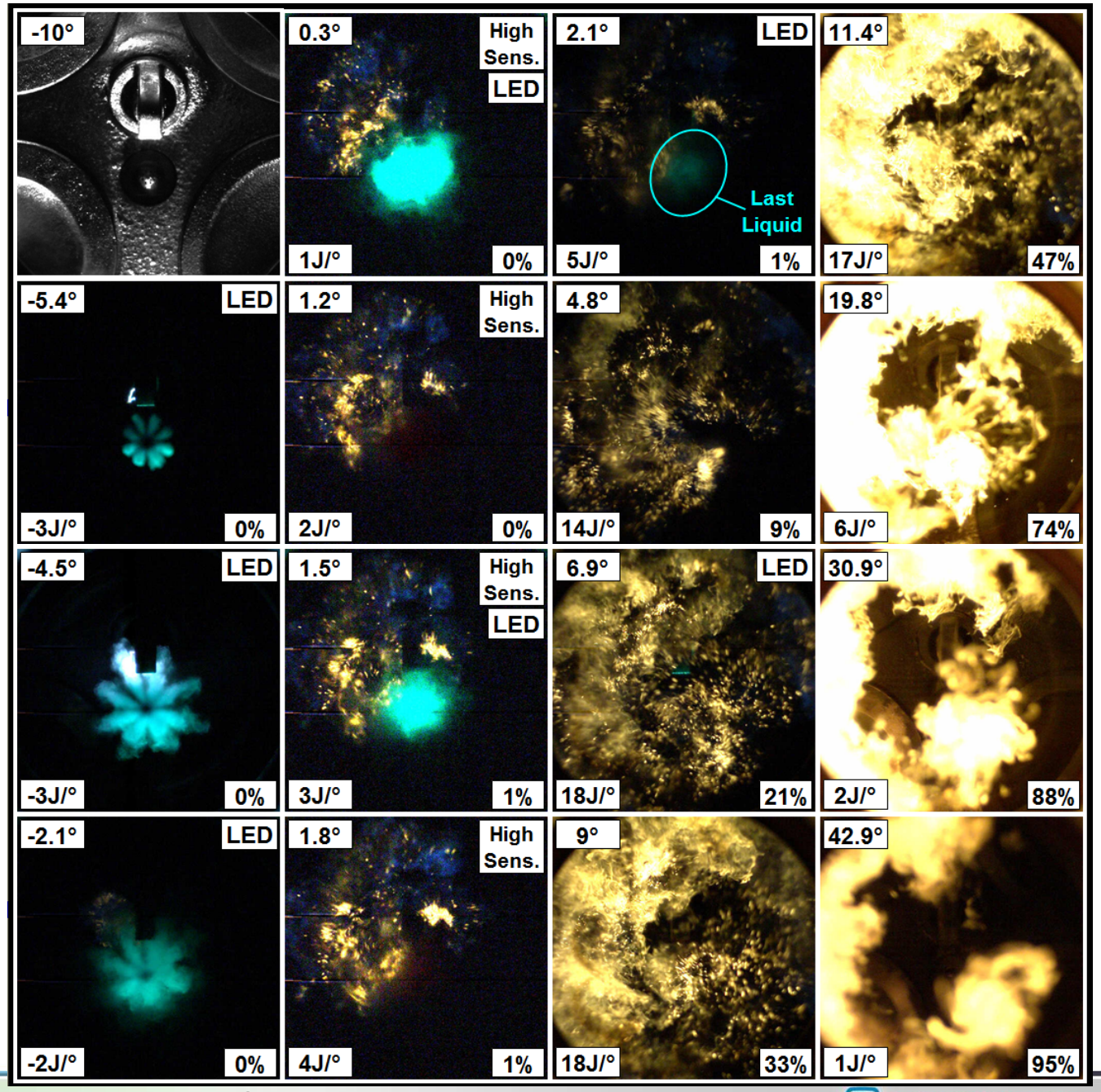




Color High-Speed Imaging

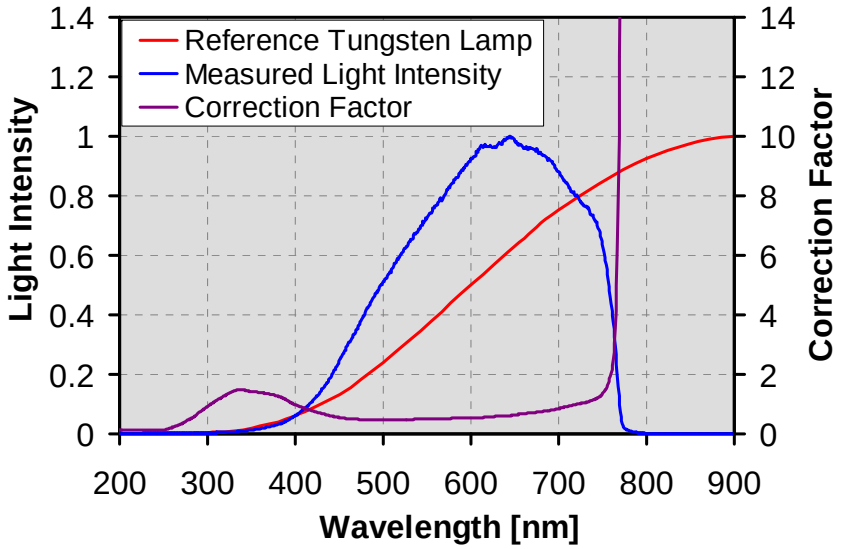
- Blue-green LED.
- Early weak flames are bluish.
- Later combustion is dominated by yellow luminosity.
- Use spectrograph to better understand combustion mode.

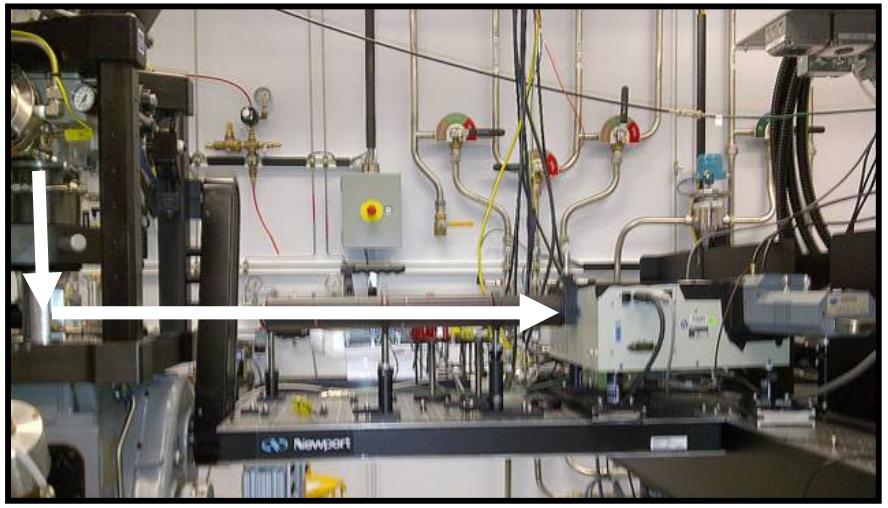
Spark = -12°CA, Intake [O_2] = 19%, Exhaust NO = 6 ppm



Spectrograph Setup

- Projecting combustion luminosity via Bowditch mirror onto spectrograph slit.
  - Coarse grating with 122 lines/mm, blazed for 413 nm.
  - Low resolution, but useful for obtaining an overview of the light characteristics.
  - Calibrated with Tungsten lamp.
  - Sensitivity goes to zero near 800 nm. Large correction ⇒ inaccurate data >780nm.
- Conditionally average from 50-cycle samples, to obtain typical spectra.

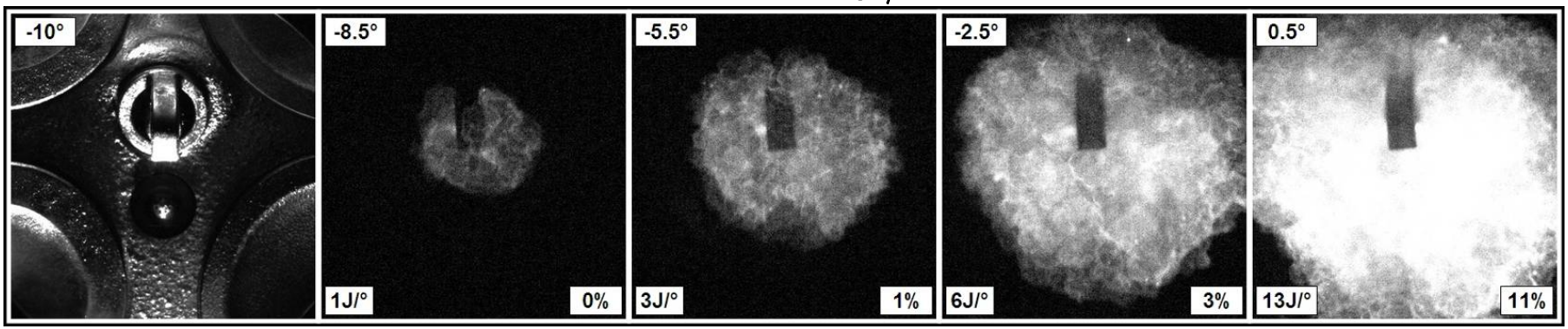




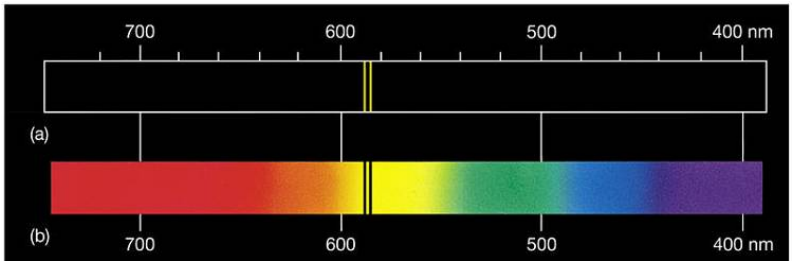
Well-mixed Spectral Response

- First examine well-mixed operation for various ϕ.
- Acquire spectra near CA10, which is when flames reach edge of view.

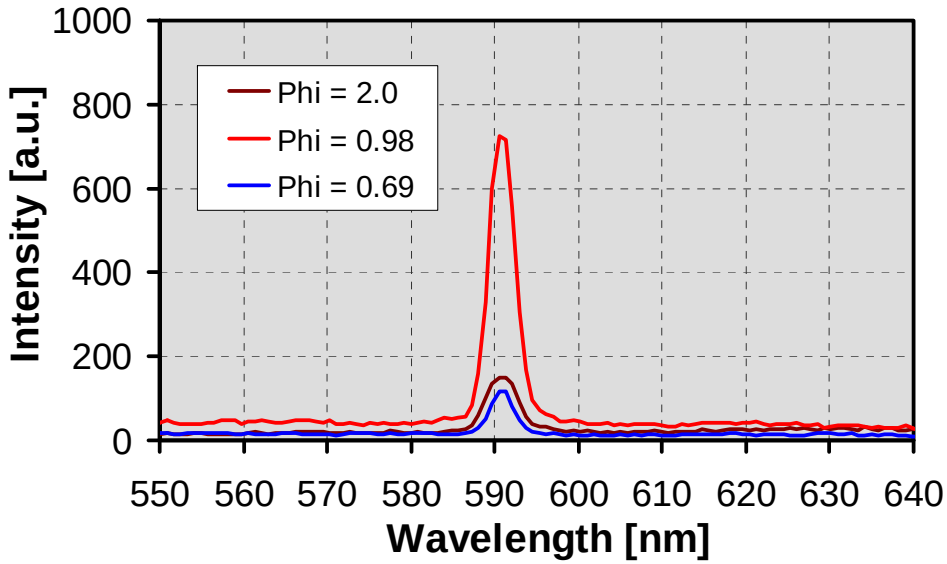
SOI = -300°CA, ϕ = 1



- Emissions lines near 590 nm
- Indicates high sodium (Na) content of the E85 fuel.

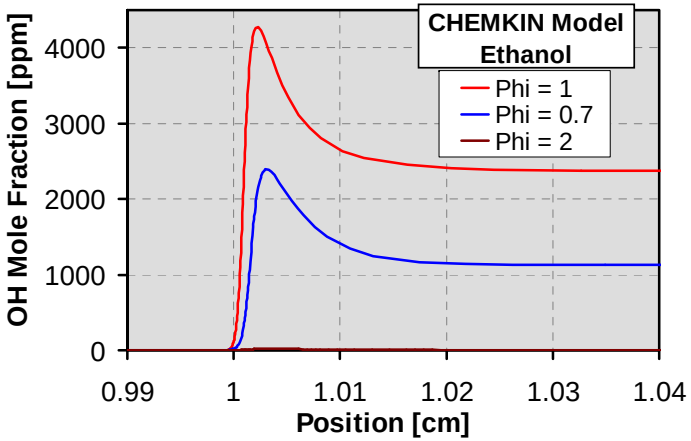


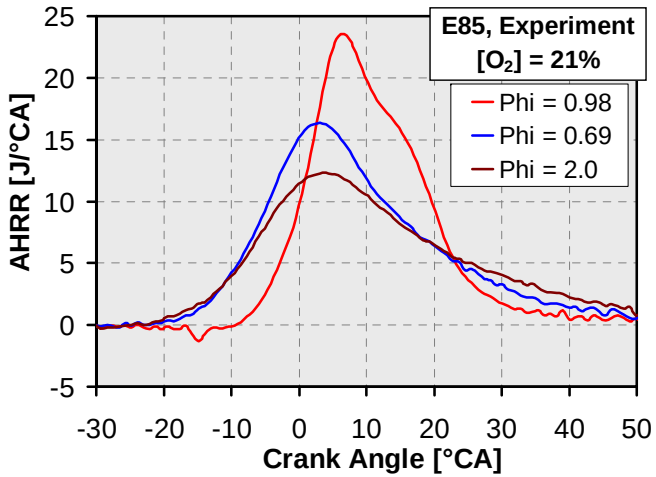
- GM paper reports on the use of sodium-enhanced luminosity.
  - SAE 2011-01-1281

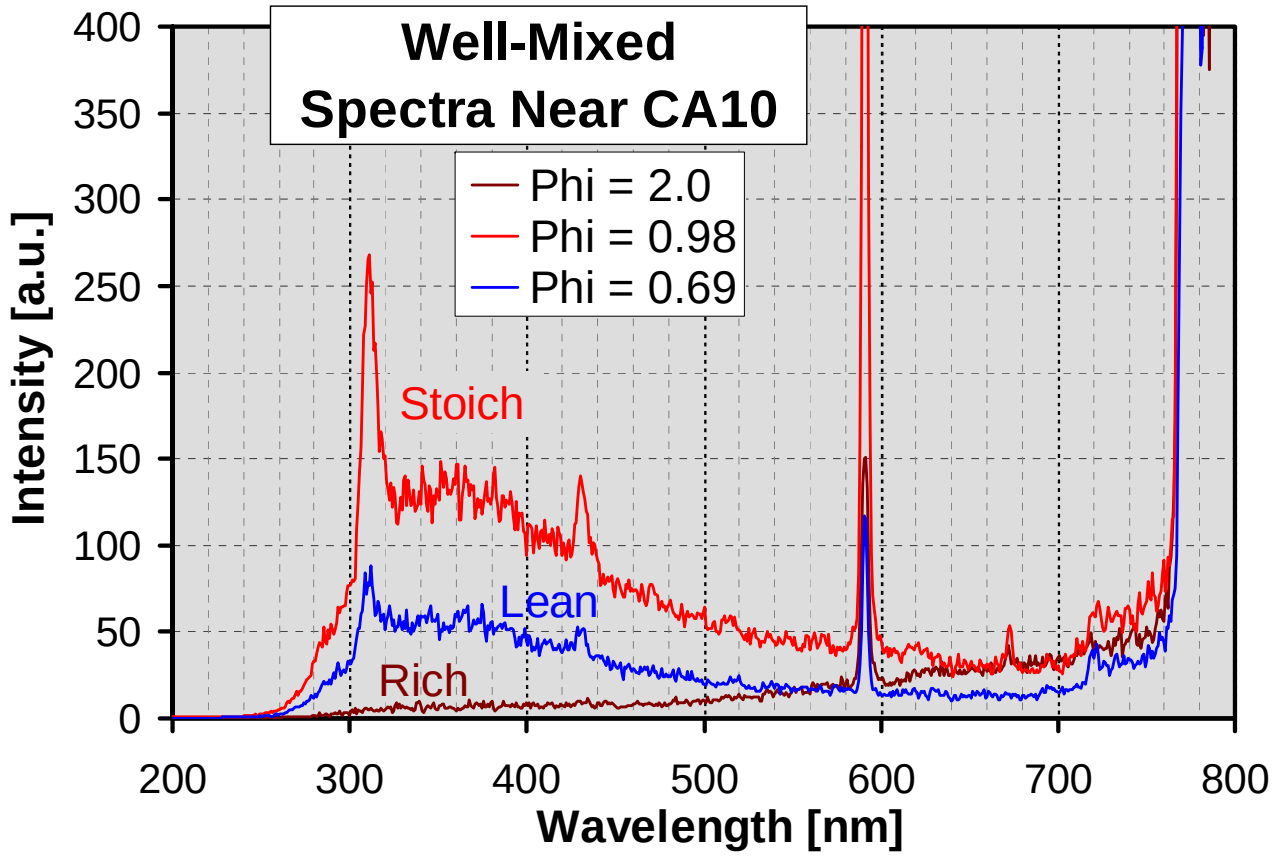


Well-mixed Spectral Response (2)

- 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.
  - Slow with low HRR.

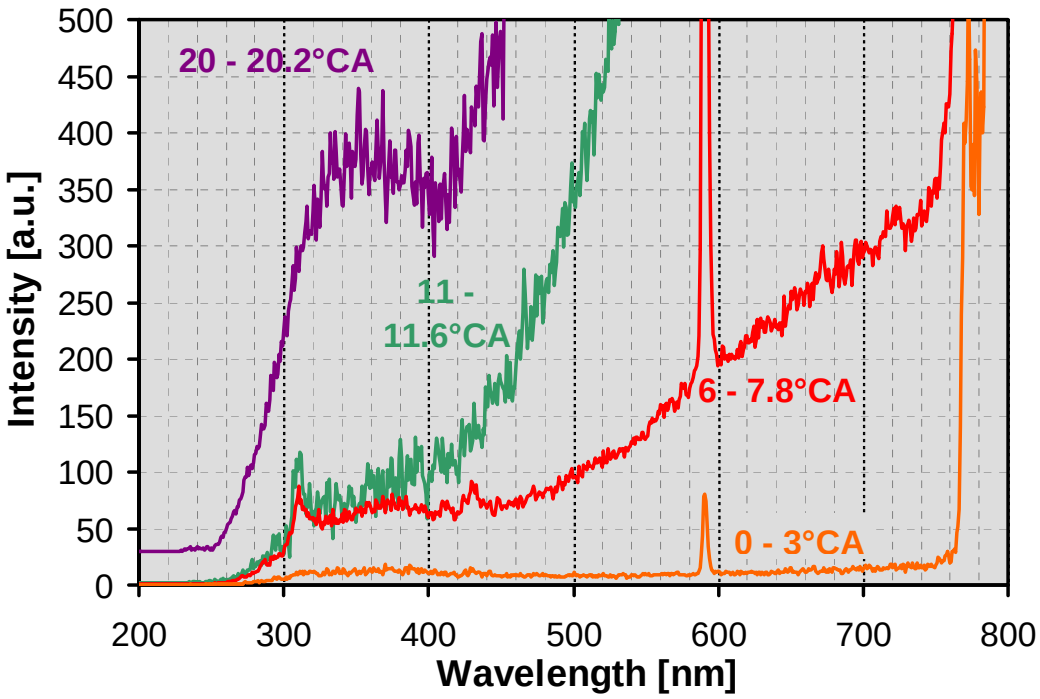


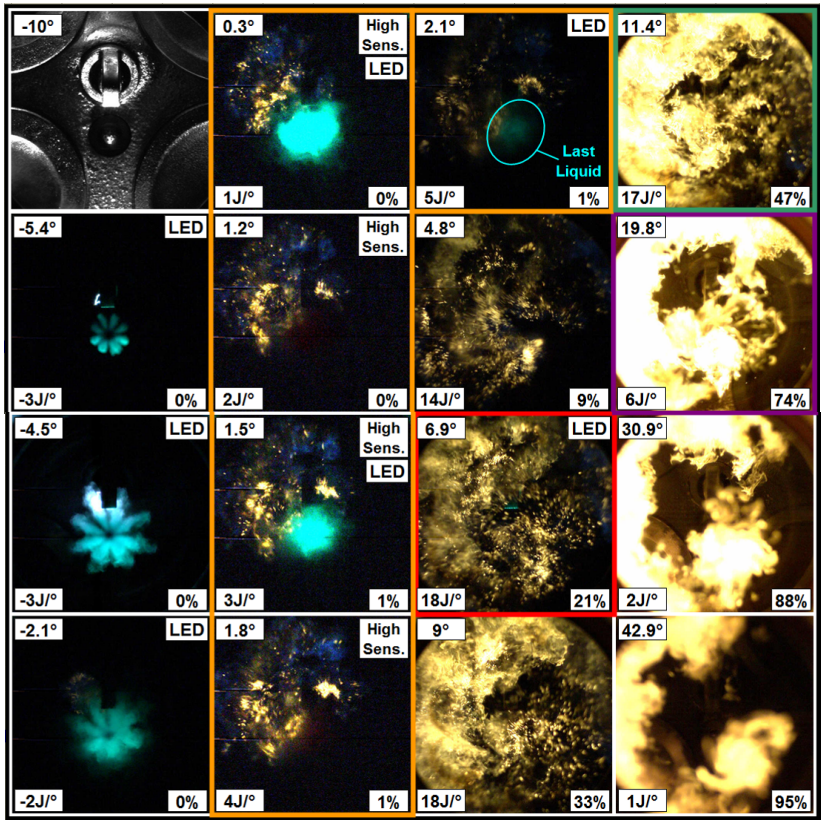




Stratified Spectra

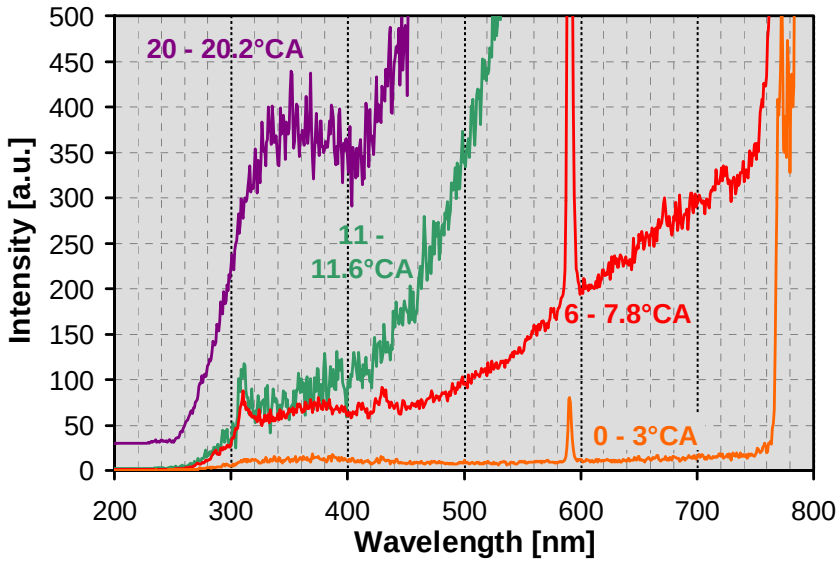
- Early luminosity is weak, and shows no peak around 308 nm.
  - Indicative of exclusively rich combustion?
- From 6° to 11°CA, distinct peak near 308 nm.
  - Substantial amount of stoichiometric and lean combustion.
- Gradual increase of black-body emissions.
- Burnout phase shows a combination of a broad peak near 350 nm and strong black-body radiation.

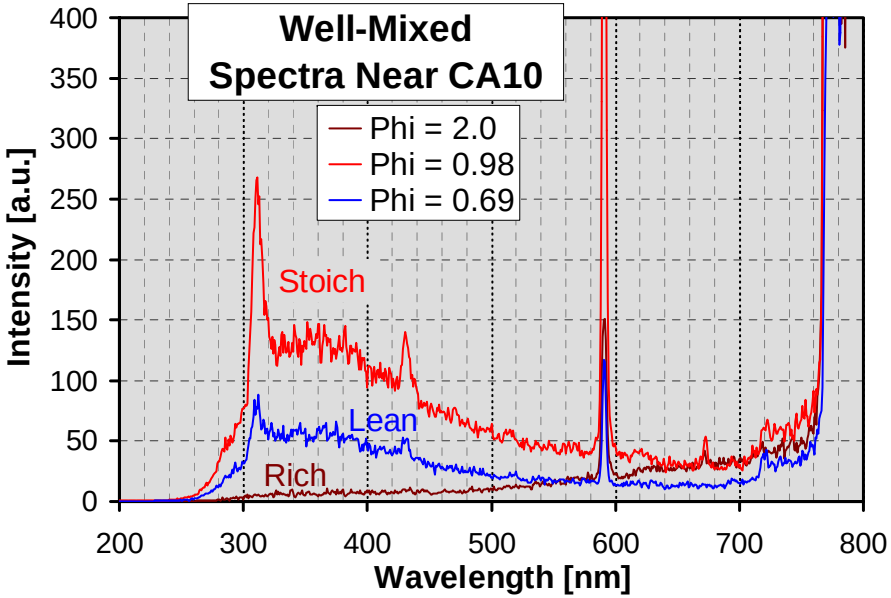


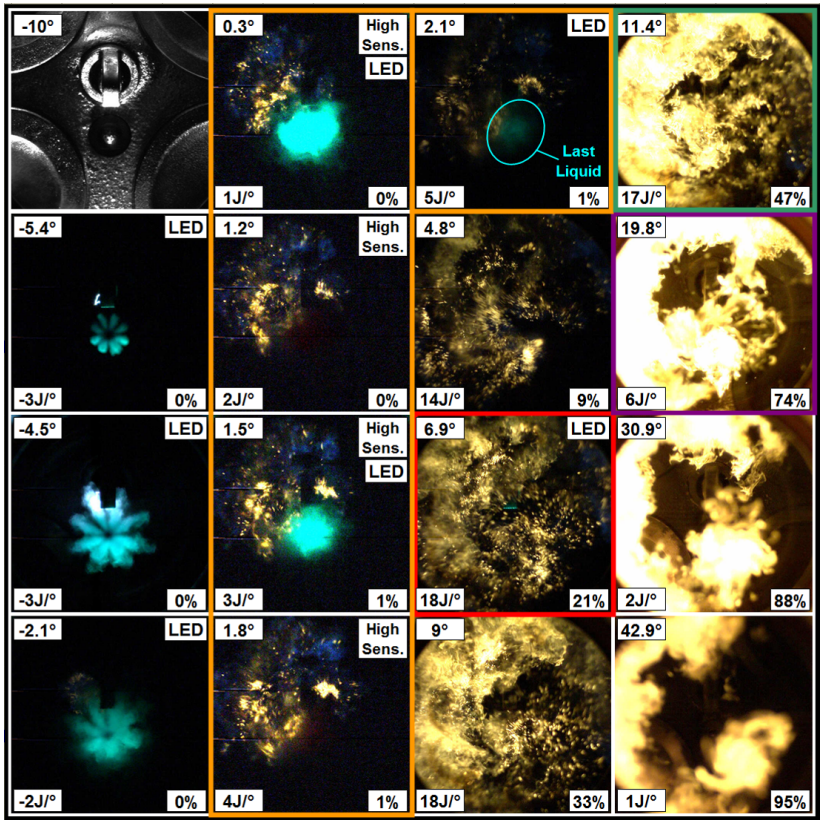


Early Combustion

- Early luminosity is weak, and shows no peak around 308 nm.
- Comparison with well-mixed spectra indicates exclusively rich combustion.

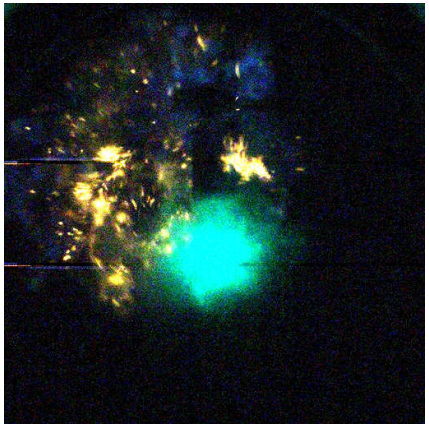


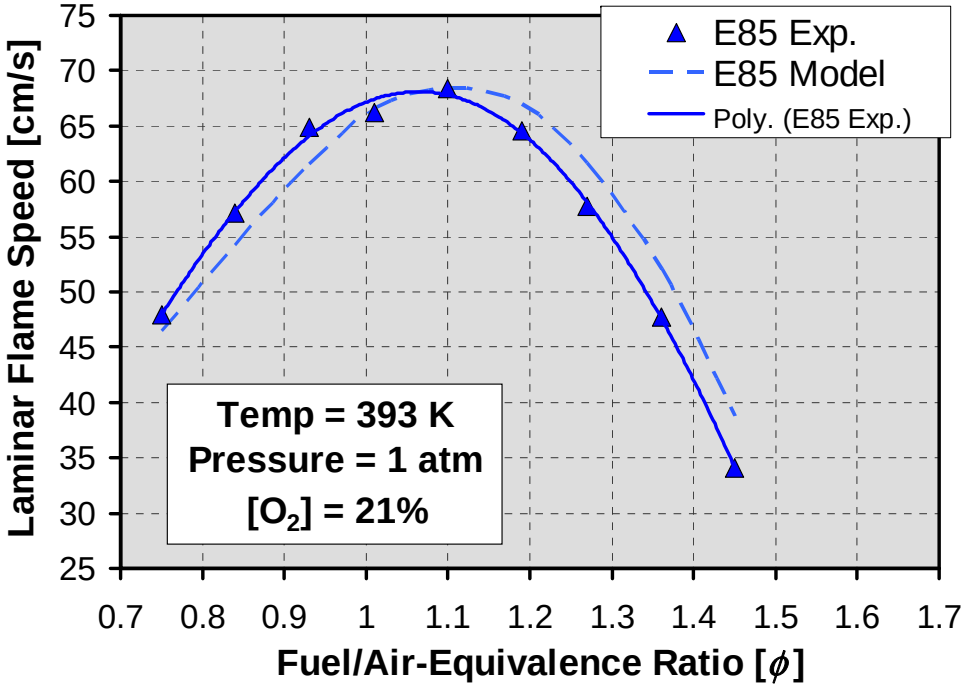


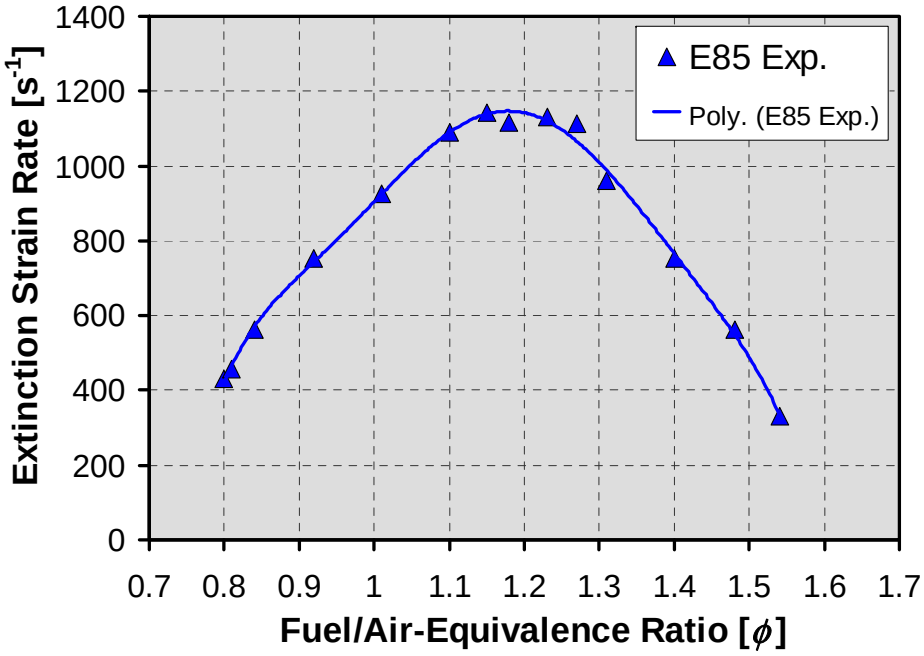


Early Combustion

- Flame speed and extinction measurements shows that E85 flames are strongest for rich mixtures.
- This adds support to the idea that the early combustion is predominantly rich.
- Survives the early strong turbulence and shear by existing in rich regions.

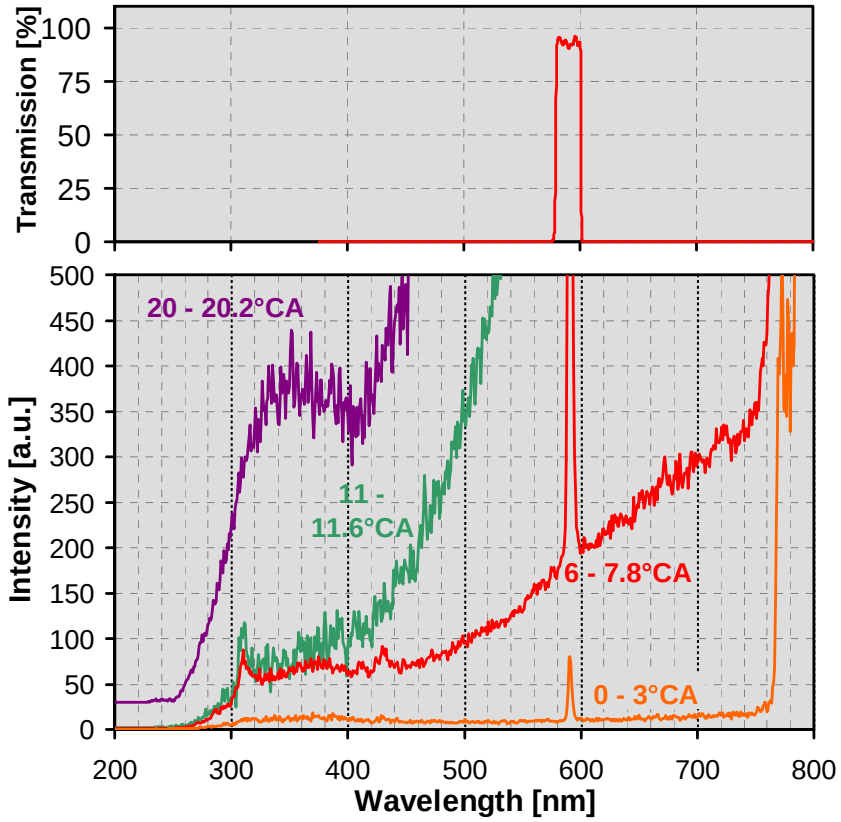


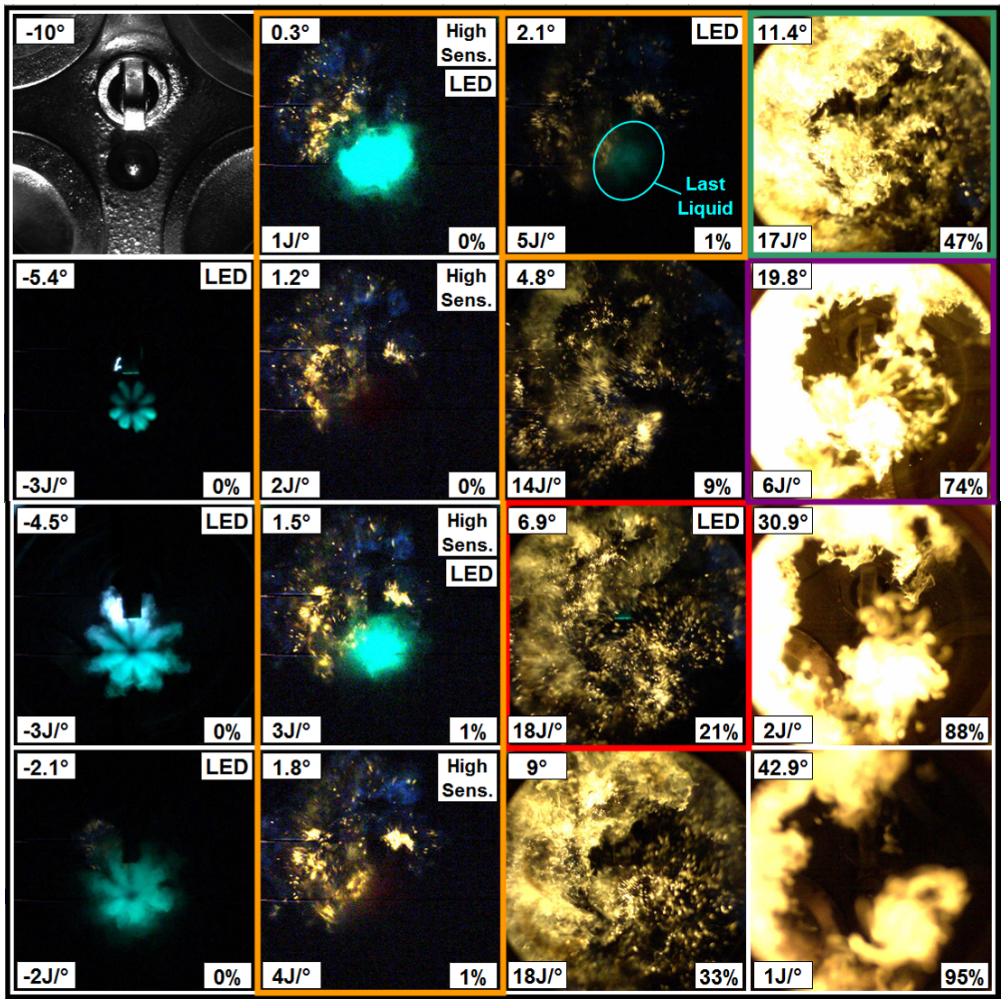




Speak and Streaks

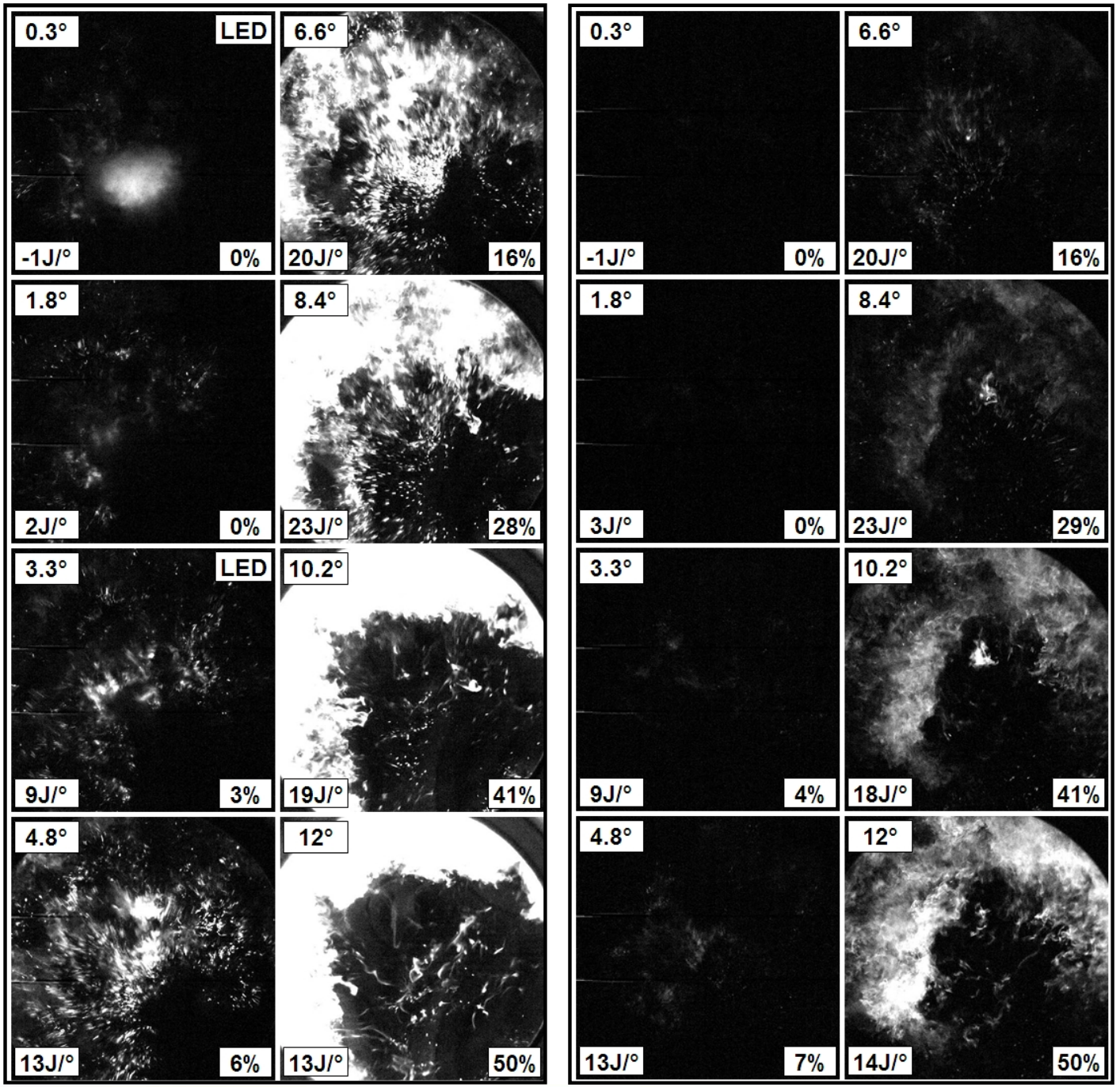
- Flame structure has fine features in 4 – 9°CA range.
- Sodium particles?
- Use narrow band-pass filter to examine.





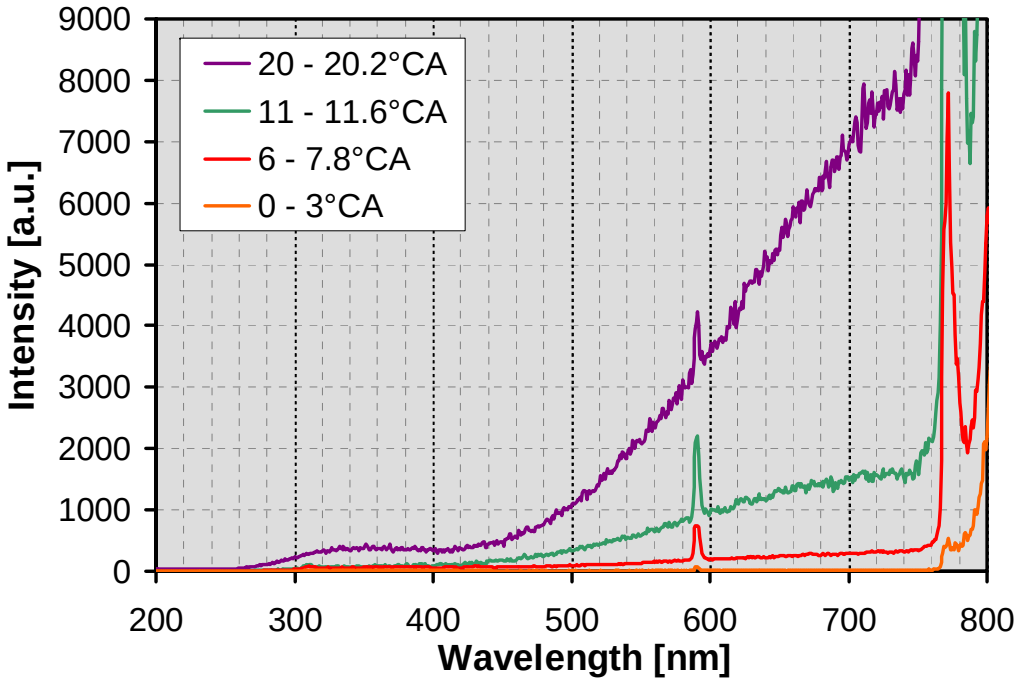
Broadband Na-Filter

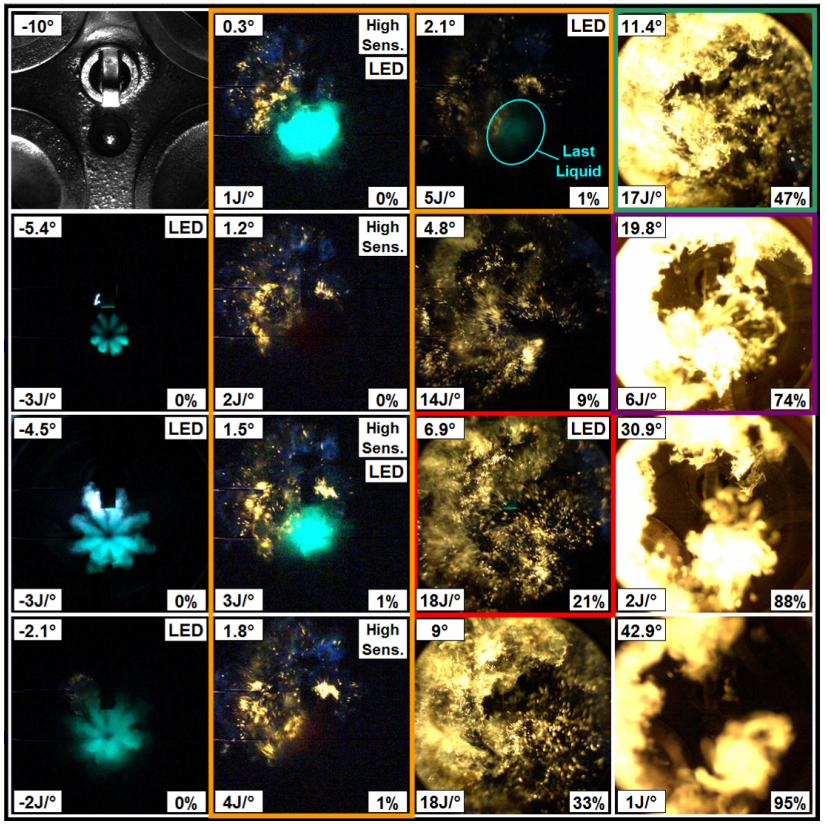
- Monochrome v710 camera + narrow band-pass filter.
- Specks and streaks are not Na-based.
- Likely soot particles.

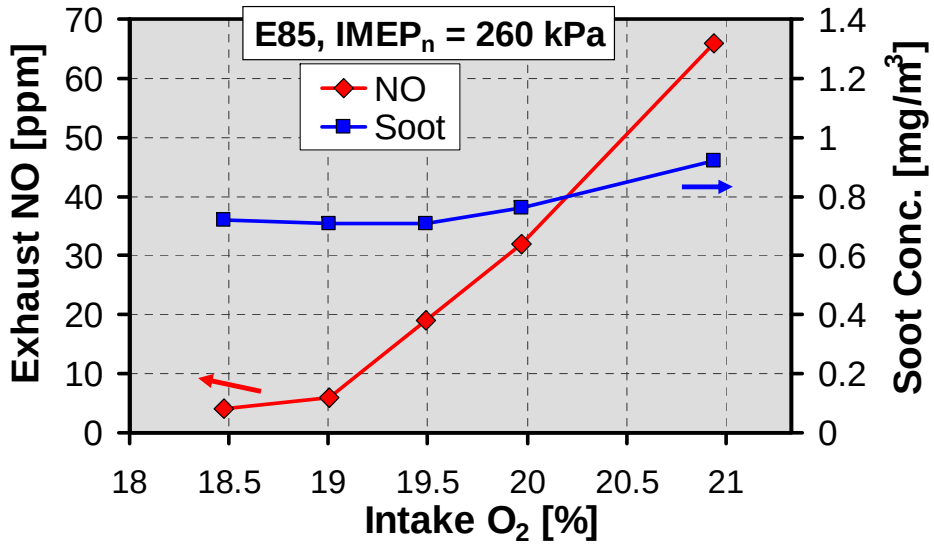


Late Spectra

- Late luminosity is bright, and dominated by black-body radiation.
- Indicative of soot.
- Engine-out soot levels are low.
  - FSN = 0.053 to 0.068
- Either peak soot levels are relatively low, or burn-out is effective.
- Exhaust soot goes up with $[O_2]$.
  - Soot formation increases faster with $[O_2]$ than soot oxidation.





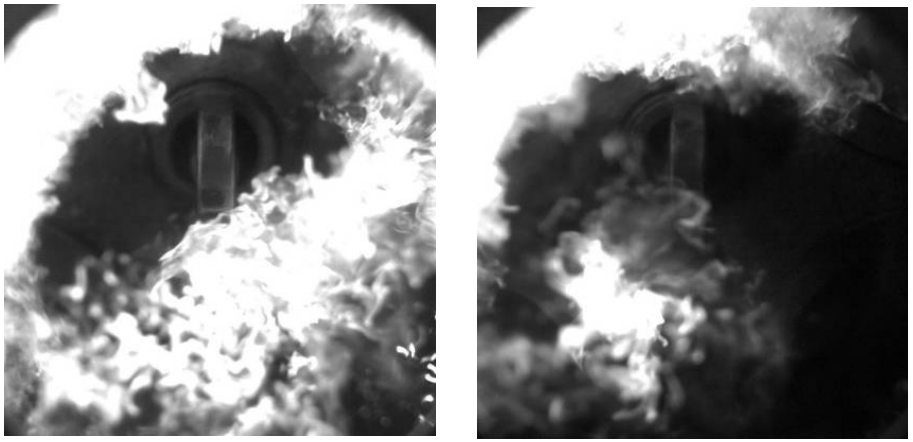


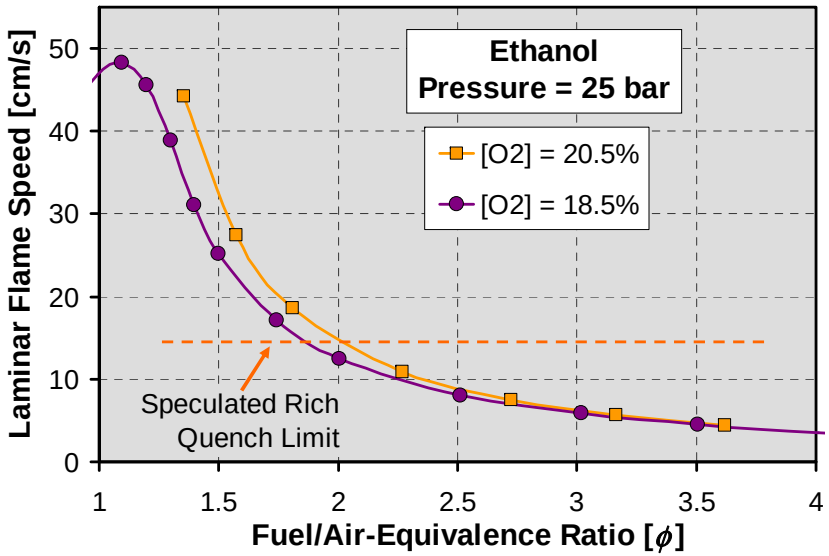
$[O_2]$ vs. Soot Production

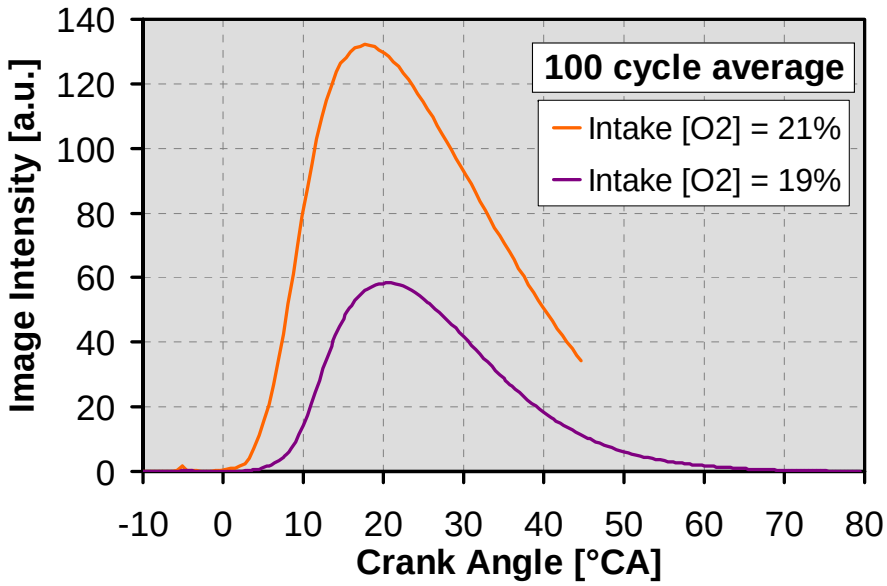
- Peak combustion luminosity is much higher for the non-diluted case.
- Suggests that the soot production is controlled by flame spread into rich regions.
- Model predicts that richer mixtures can burn for non-dilute case.
- Luminosity goes to near-zero late.
  - Burn-out and cooling.

Intake $[O_2]$ =

21% **19%**







Summary

- Stratified spray-guided DISI combustion can provide substantial fuel savings.
- E85 responds favorably to SOI retard ⇒ enables very low exhaust NO and soot.
  - Lower peak temperatures, and less residence time.
- Stable operation with near-TDC fuel injection is possible for E85.
  - **E85 allows spark ignition of the head of the fuel jets**, and strong spray/plasma interactions create large amounts of early flame spread prior to onset of main heat release.
- Spectroscopic work indicates that the early combustion is exclusively rich.
- Consistent with measurements and predictions of flame speed and extinction.
- Bright specks and streaks are not caused by Na in fuel, rather burning soot particles.
- Combustion spectra show that the main combustion produces significant amount of soot.
- Regardless, exhaust soot emissions are relatively insensitive to intake $[O_2]$.
- Less flame spread into rich regions for lower $[O_2]$ may reduce soot production, therefore balancing expected deterioration of soot oxidation at lower $[O_2]$.