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COMBUSTION RESEARCH FACILITY

Utilizing Boost and Double Injections for Enhanced Stratified-Charge DISI Operation with Gasoline and E30 Fuels

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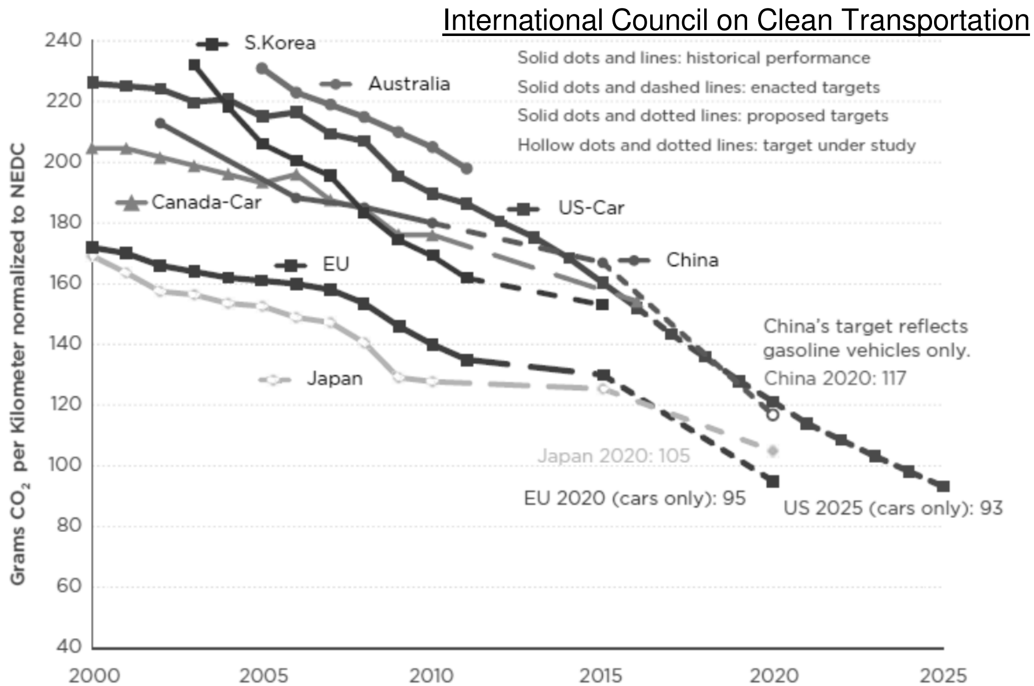
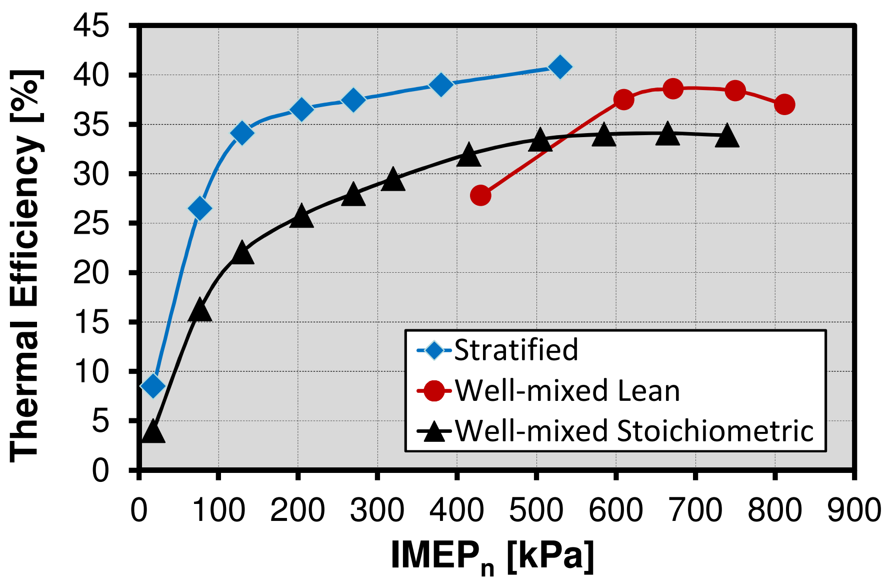
U.S. DEPARTMENT OF ENERGY

Co-Optimization of Fuels & Engines

Introduction

- Strong pressure to reduce CO_2 emissions.
- Improved engine efficiency is one key factor.
- Stoichiometric SI operation is standard for gasoline-type engines.

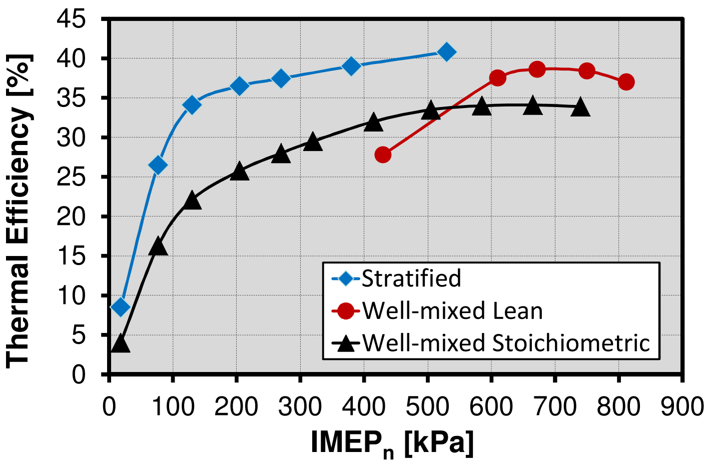


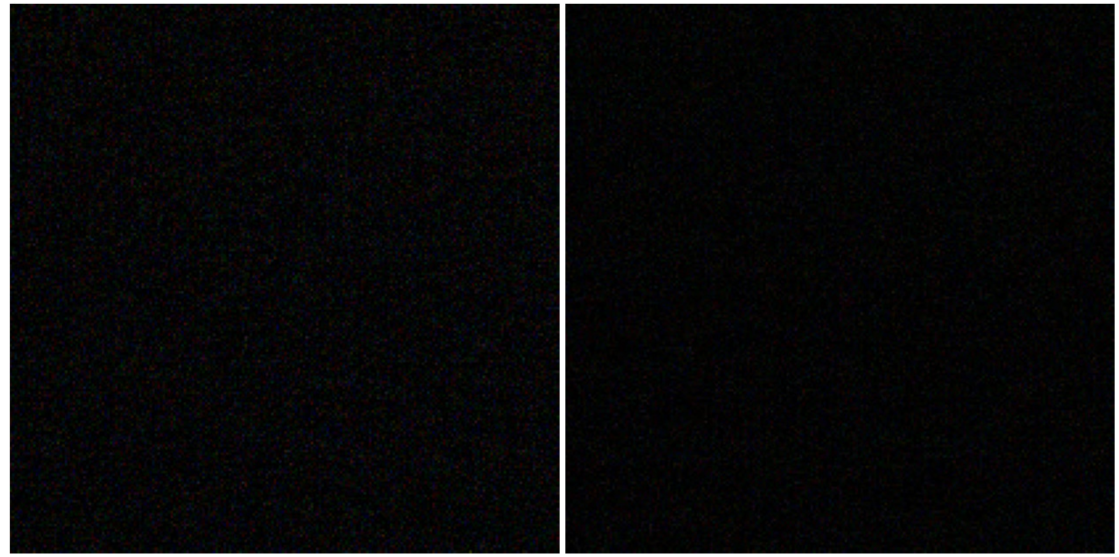


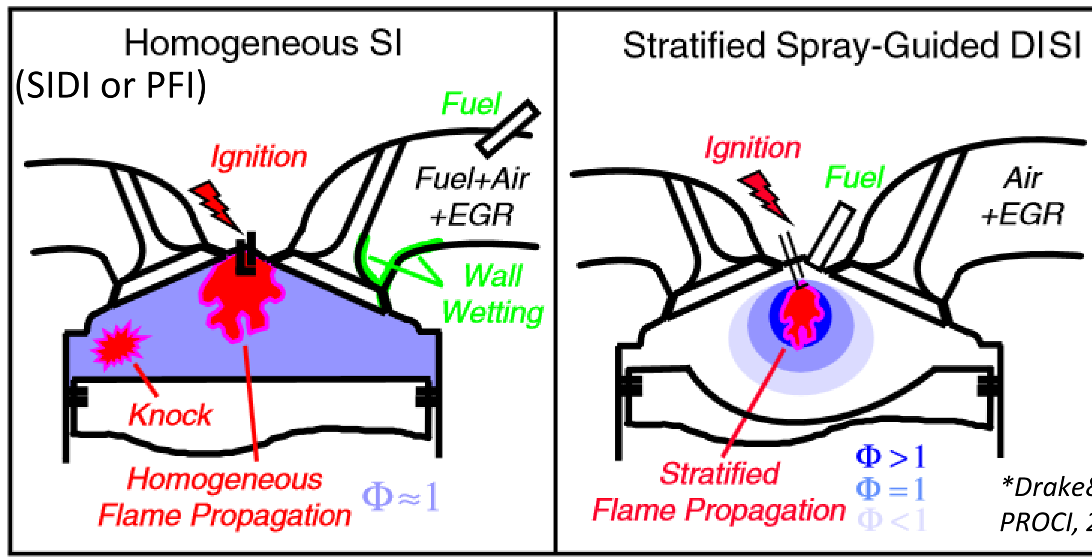
- Lean operation may well be required to for SI engines to meet CO_2 requirements.
- Stratified-charge operation has strongest efficiency potential.

Stratified vs Well-Mixed Stoichiometric

- High TE can be achieved in SI engine using un-throttled stratified-charge combustion at low to moderate loads







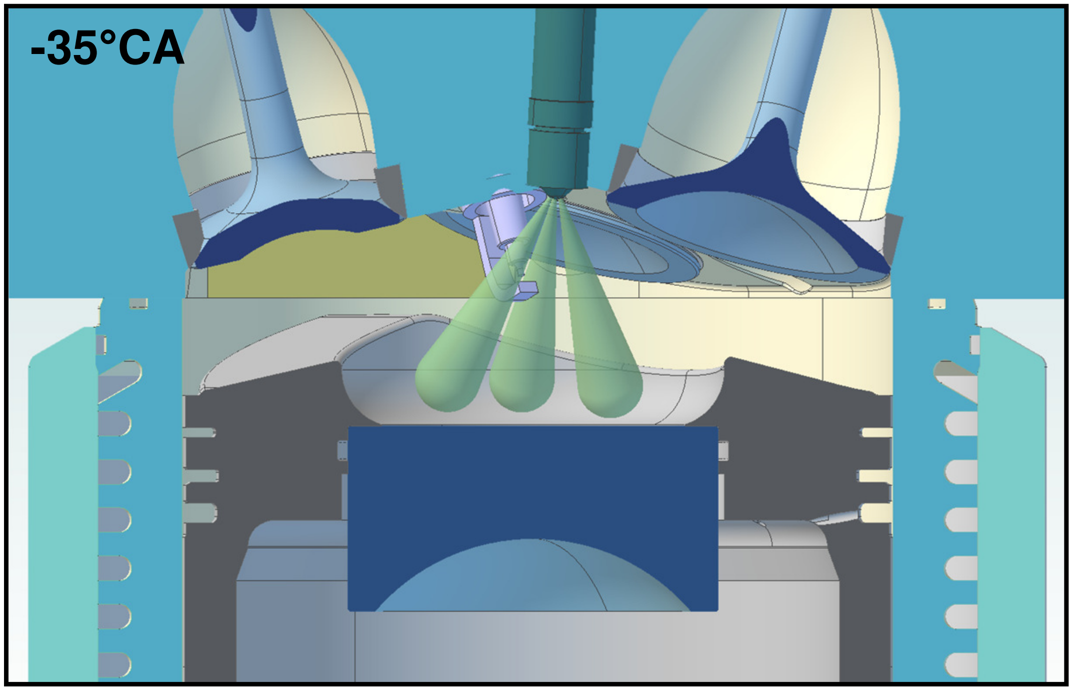
*Drake&Haworth PROCI, 2007

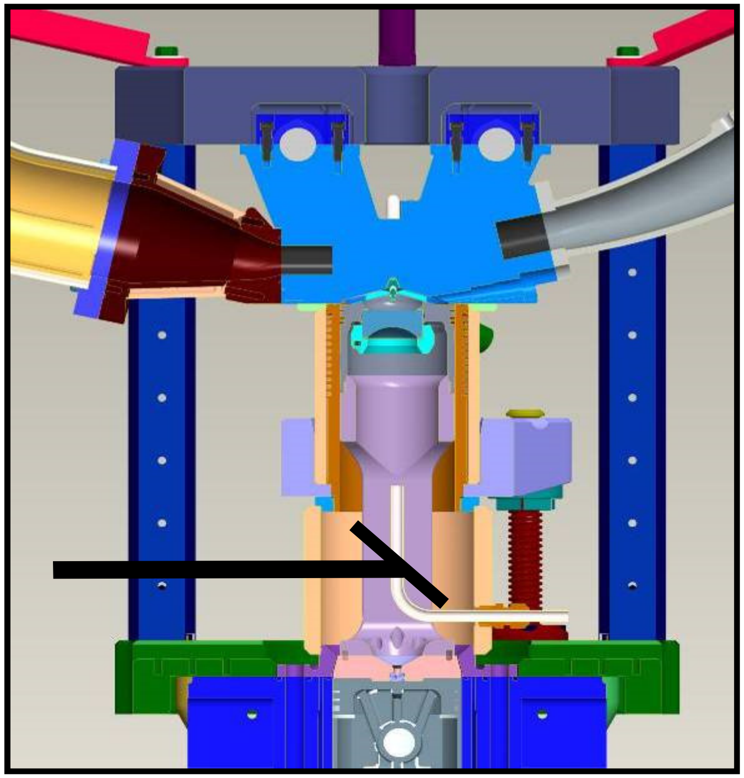
Throttled flow rate control
well-mixed stoichiometric
(Knock, pumping loss)

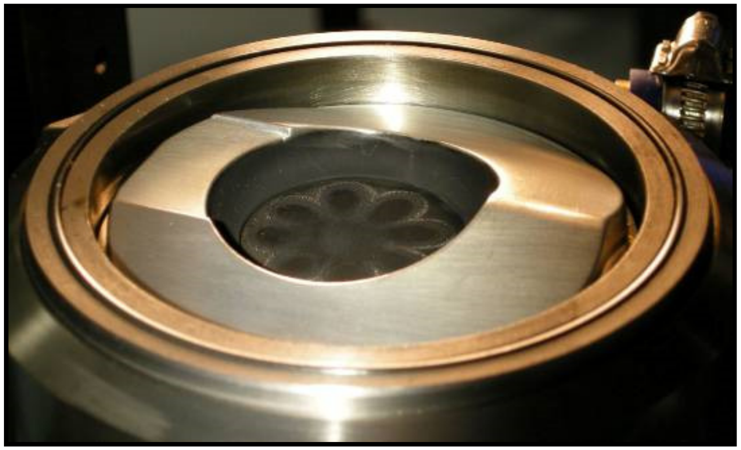
Un-throttled load control
overall-lean
(Soot, NO_x, CCV)

Research Engine

- Designed for spray-guided stratified-charge operation ⇒ Piston bowl.
- 8-hole injector. P_{in} = 170 bar.
- Drop-down single-cylinder engine.
- Automotive size. 0.55 liter swept volume.
- Identical geometry for **All-metal** and **Optical.**

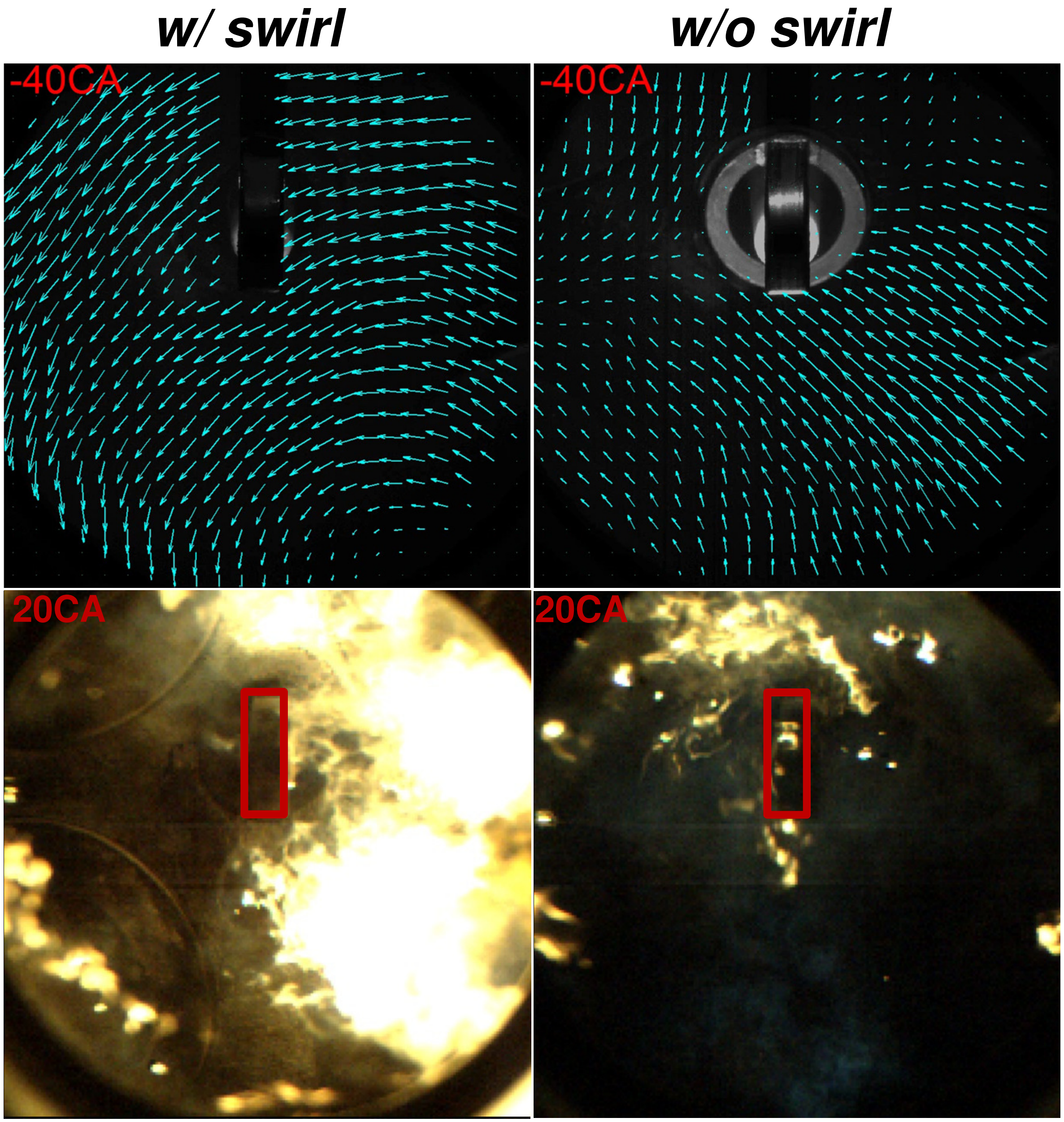




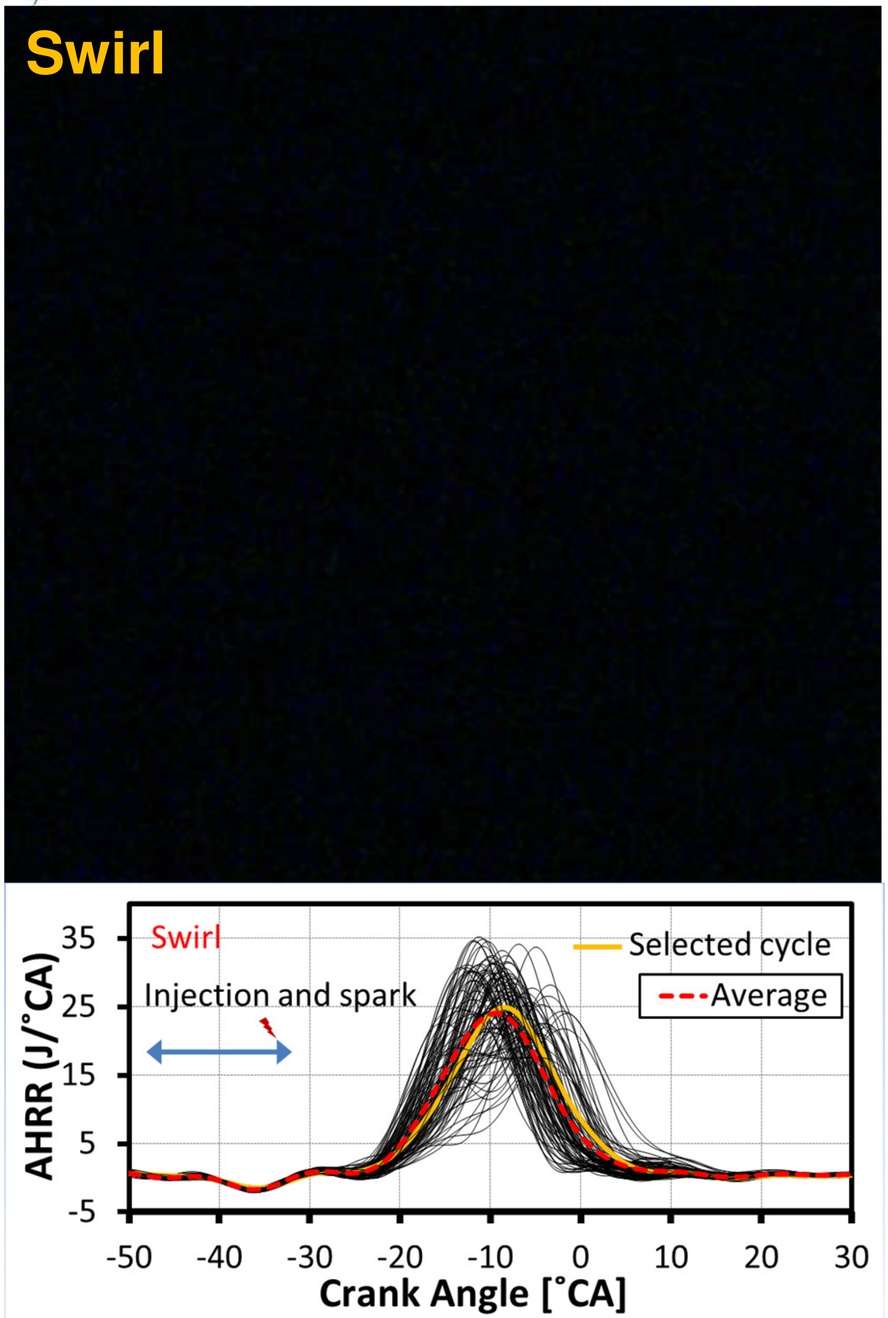


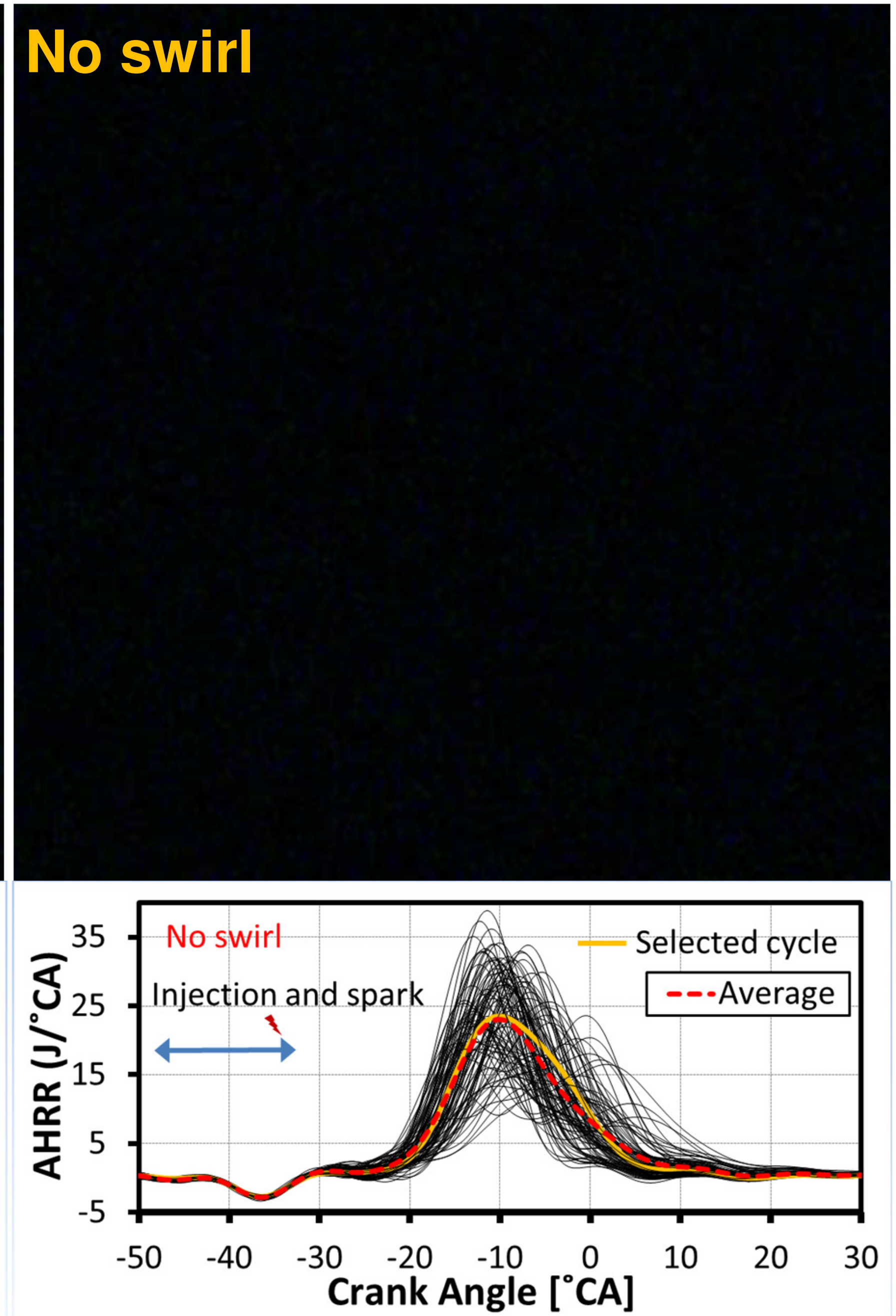
Swirl Flow Stabilizes Combustion

- Swirl-spray interactions for stabilizing stratified combustion
  - Creates a strong and repeatable vortex.
  - Effective flame propagation.
- Swirl generated by inactivating one intake valve.
  - Increases tumble as well, which can induce fuel asymmetry and elevated soot emissions.



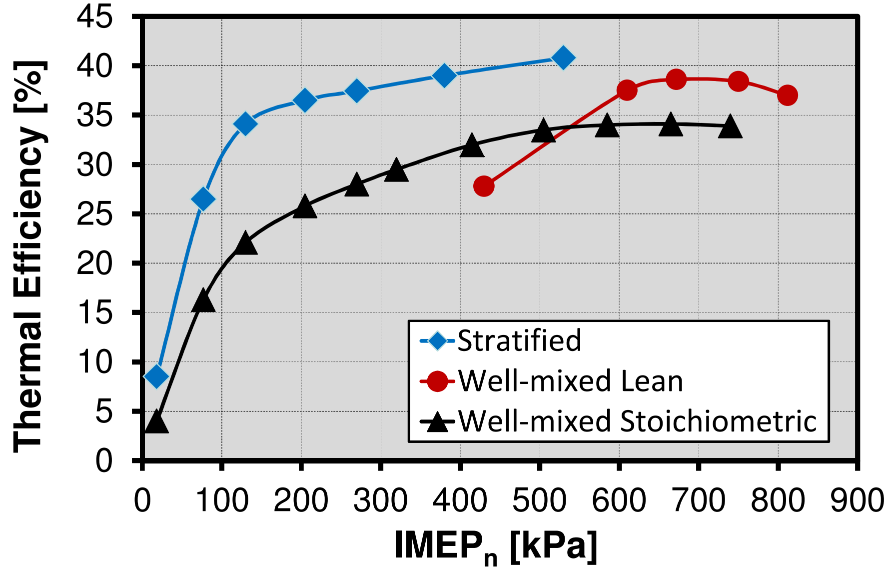
Flame propagation





Scope of Study

- To maximize fuel economy, need to ensure wide load range of stratified-charge operation.
- Turbocharging is becoming commonplace for SI engines.
  – Opportunity for wider load range of stratified operation.

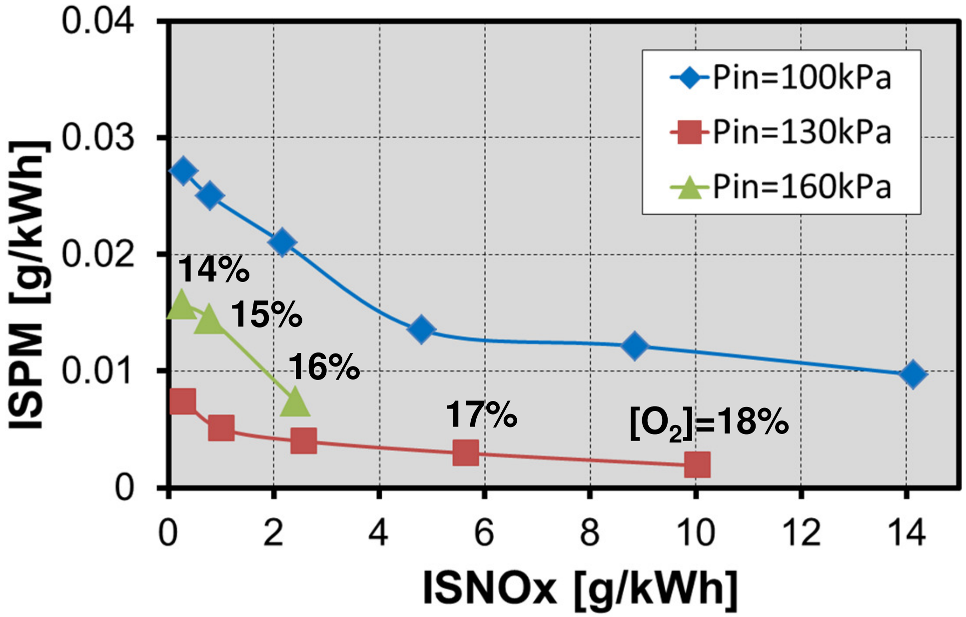


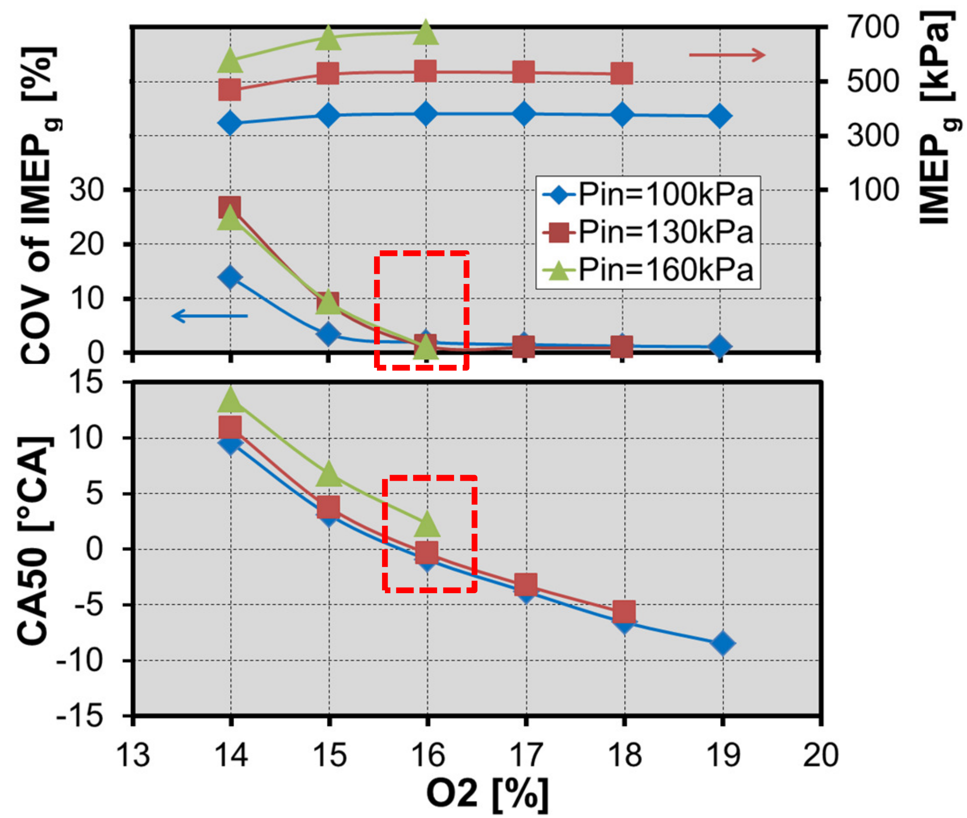
- Increased gas density influences:
  – Flow-spray interactions, liquid penetration length.
  – Fuel-air mixing, flame spread, and soot formation.
- Systematically explore boosted stratified-charge operation at 1000 rpm.
- Objectives:

1. Ensure stable stratified combustion with low NO_x and smoke.
2. Explore the benefits of double injections.
3. Assess compatibility with gasoline and E30 fuels.

EGR Sweeps – Maintain ϕ_m

- Maintain ϕ_m = 0.33, SOI = -31°CA.
  - P_{in} = 100 kPa, 12.6 mg
  - P_{in} = 130 kPa, 16.7 mg
  - P_{in} = 160 kPa, 20.8 mg
- Substantial extension of load range.
- Combustion instability prevents lower than $[O_2]$ = 16%.
- P_{in} = 130 kPa has best NO_x / PM trade-off.



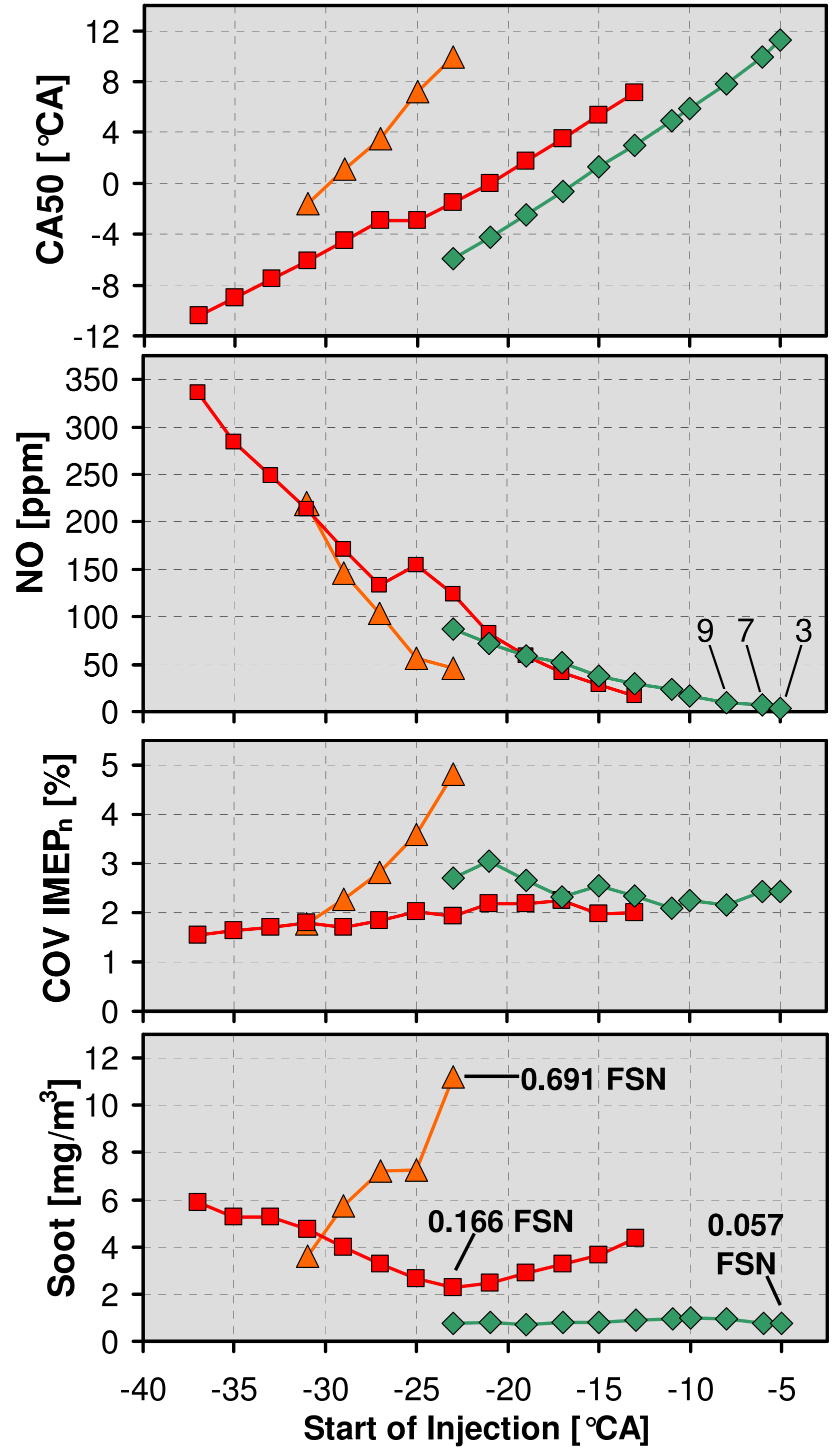


Ideally, like to retard CA50 more.

What happens to fuel distribution at high P_{in}?

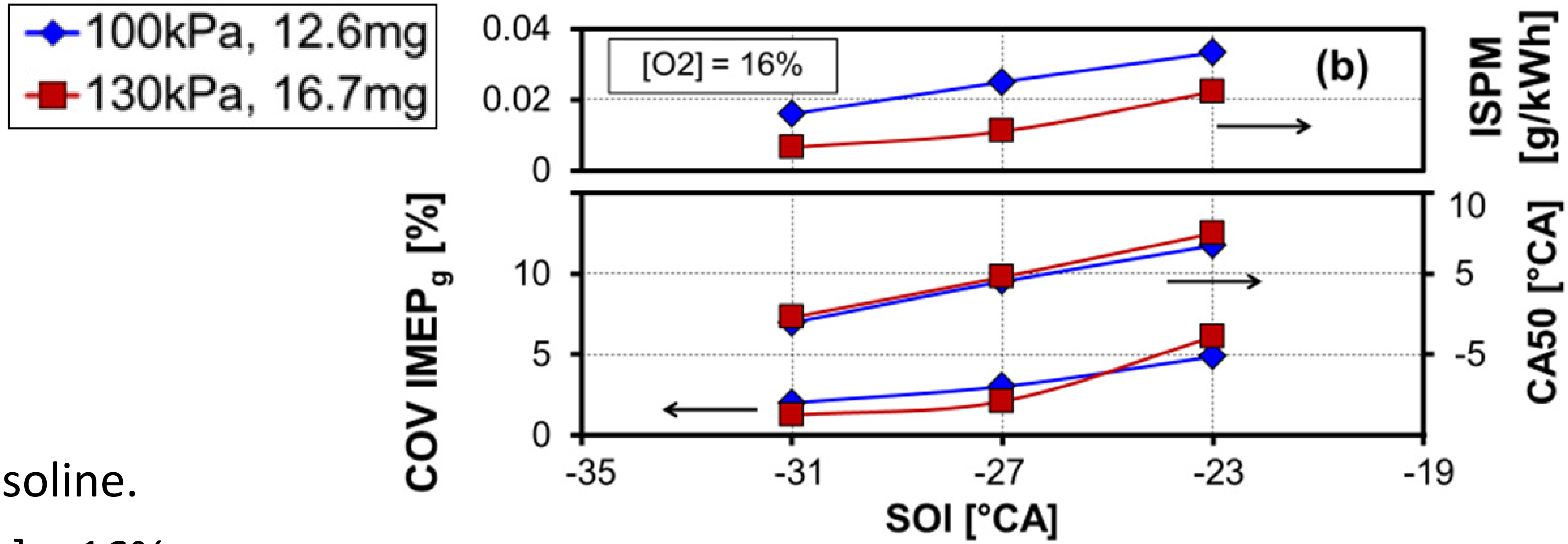
Use double injection to stabilize low $[O_2]$ operation.

SOI Retard



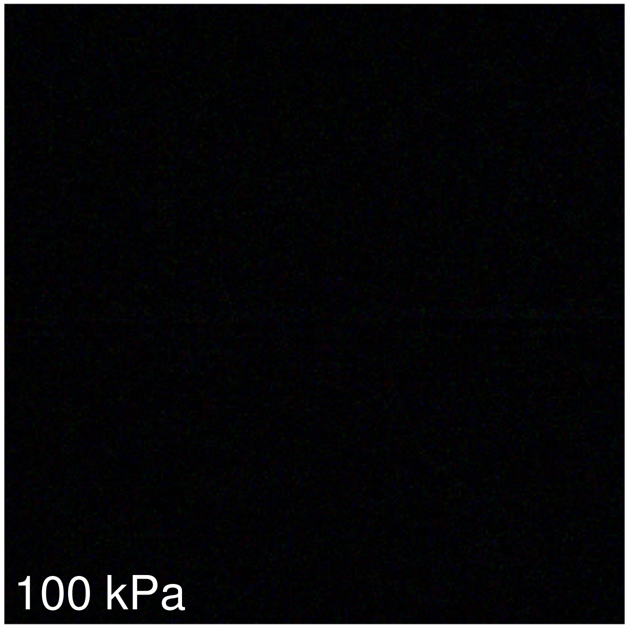
- Example for P_{in} = 95kPa, including E85.
- SOI retard can shift CA50.
- SOI retard strongly reduces NO_x emissions.
- Unfortunately, gasoline does not tolerate SOI retard.
  - Soot & COV of IMEP ⇑

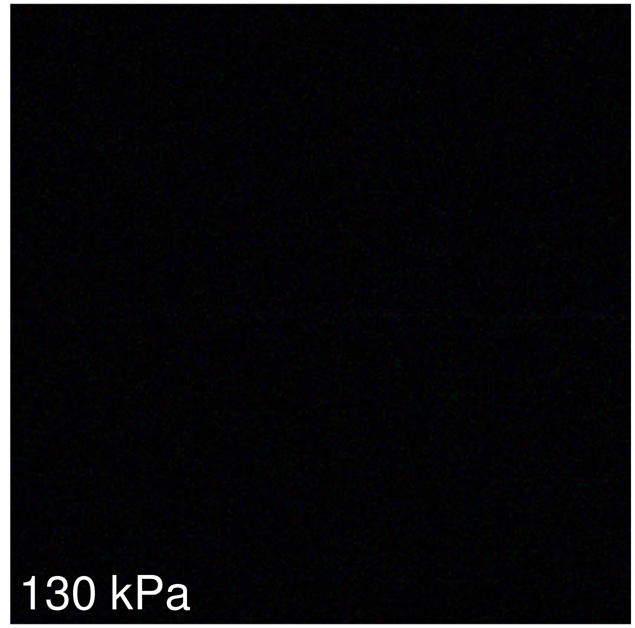
SOI Retard for Gasoline



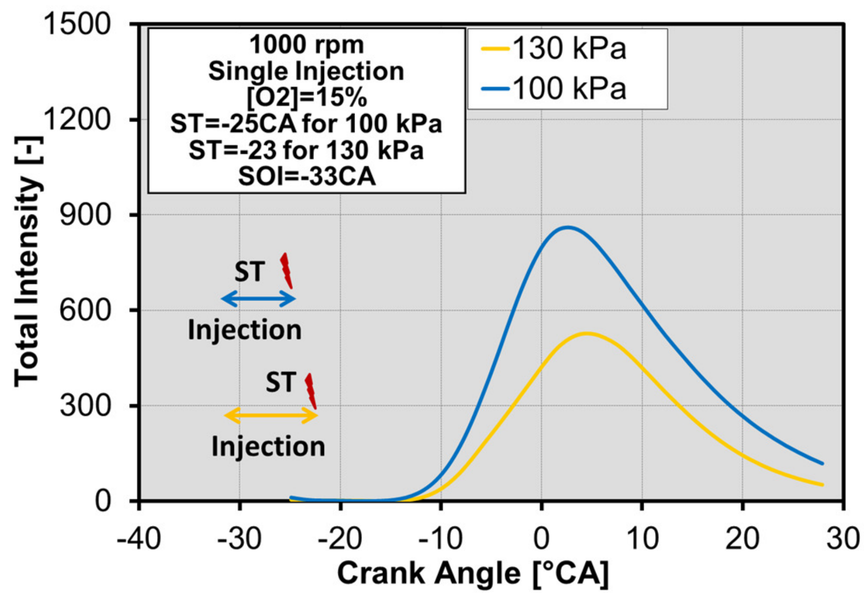
- Gasoline.
- $[O_2]$ = 16%.
- Same issues with SOI retard regardless of intake pressure.

Single Injection w/ and w/o Boosting



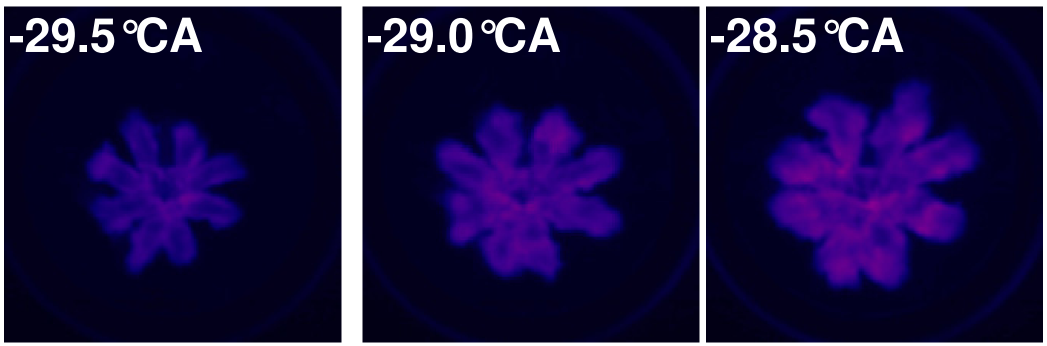


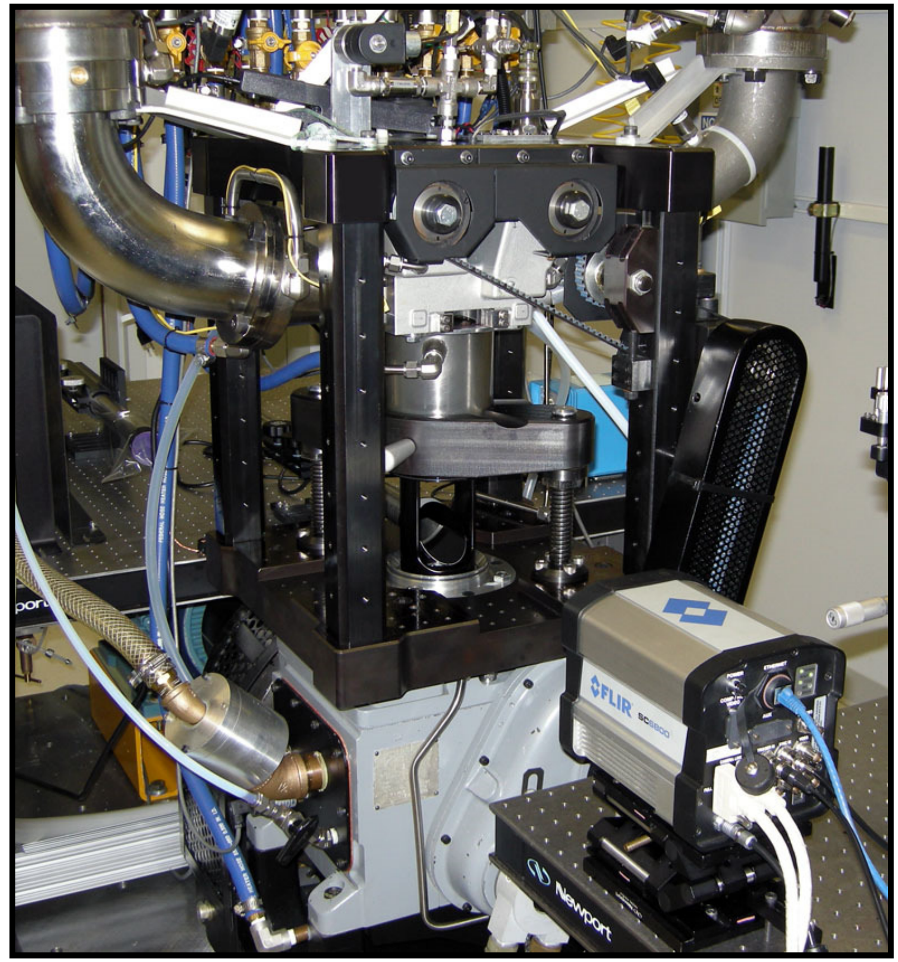
- $[O_2]$=15%, single injection.
- Clear spray collapse for longer injection at P_{in} = 130 kPa.
- Still, reduced smoke and lower flame luminosity.



High-Speed Infrared Fuel-Vapor Imaging

- Mid-infrared thermography. Band-pass filter 3.20µm ± 300 nm
- FLIR SC6800. Relatively high frame rate - 2000 Hz.
- 1 image each 3 °CA at 1000 rpm
- Phase-shifted repetitions provide 0.5°CA resolution.

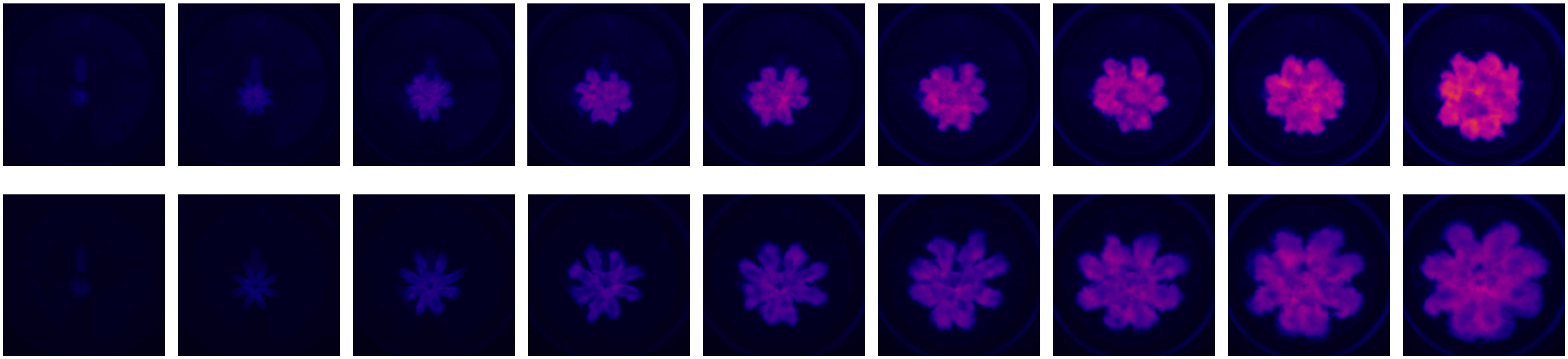




Effect of Intake Boost on Vapor Penetration

Gasoline, SOI = -31°CA, ΔCA = 0.5°

P_{in} = 187kPa.

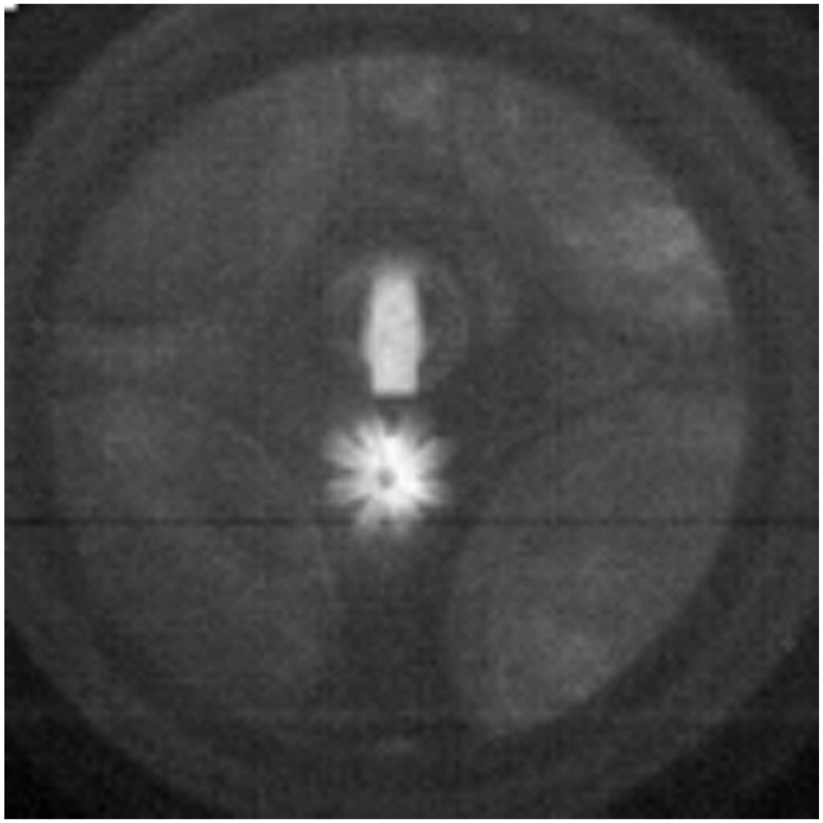


P_{in} = 98kPa.

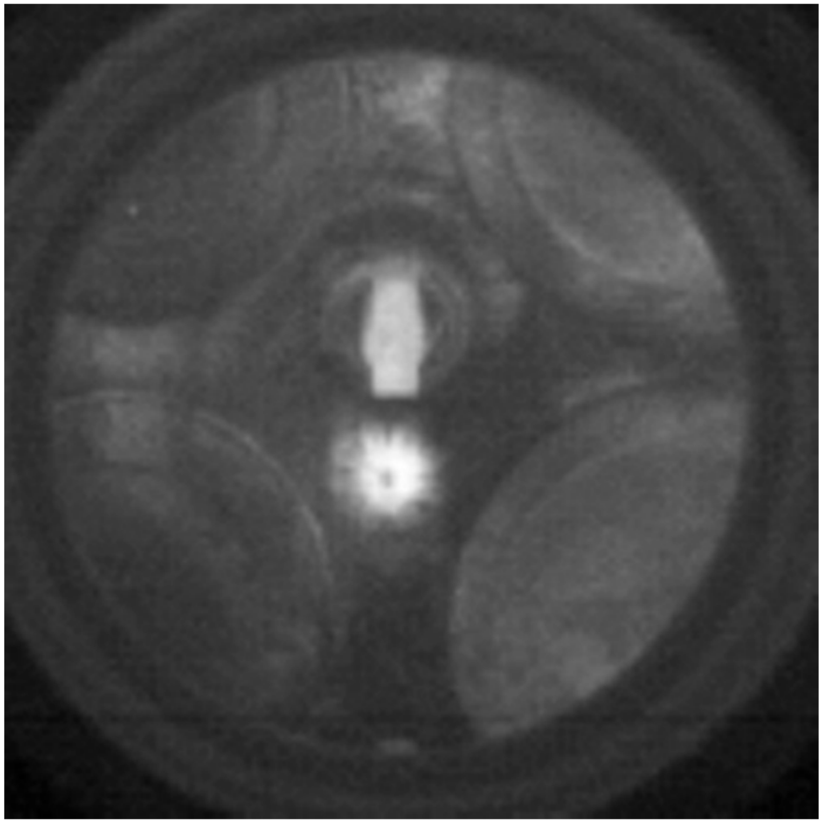
Effect of Intake Boost on Vapor Penetration

Gasoline, SOI = -31 °CA

P_{in} = 98kPa



P_{in} = 187kPa



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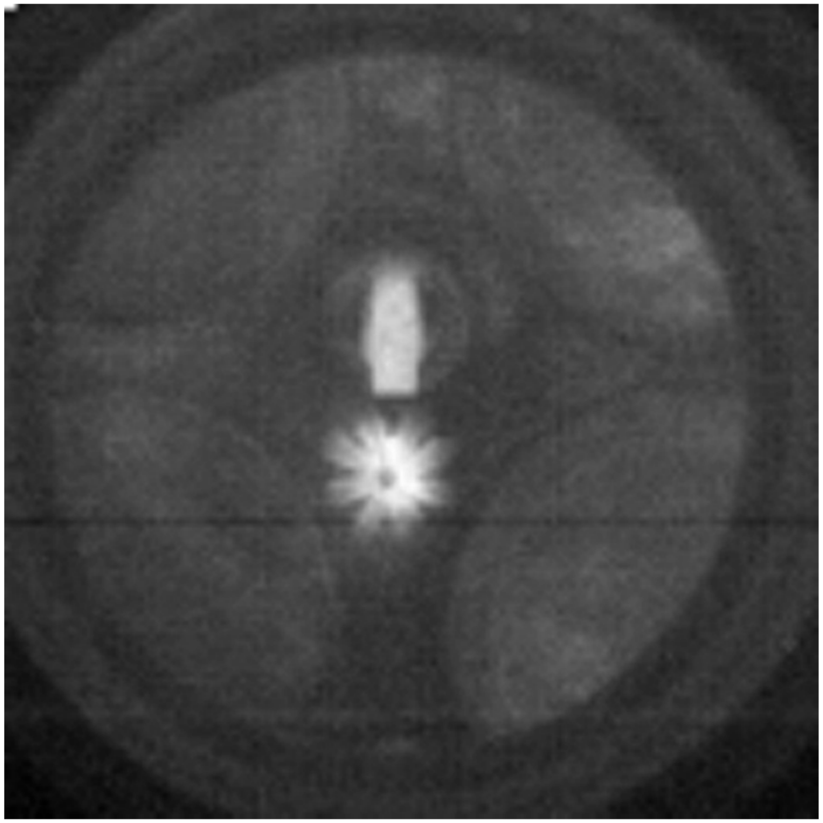
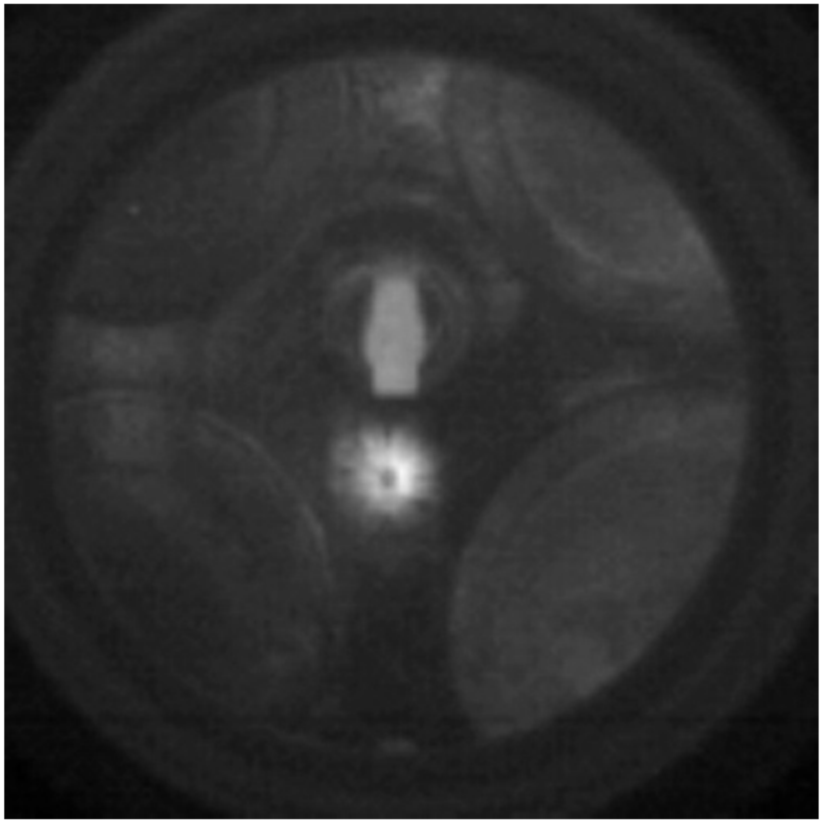
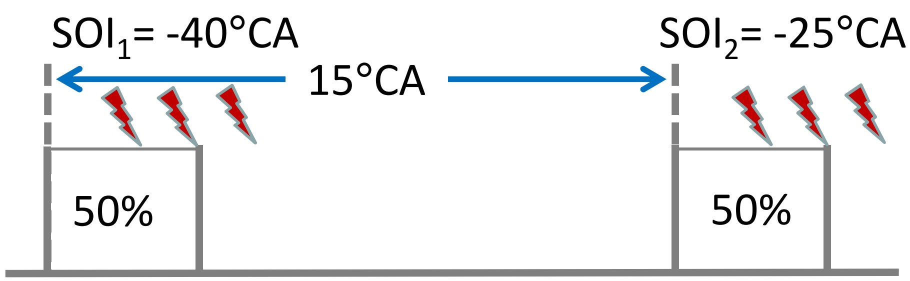


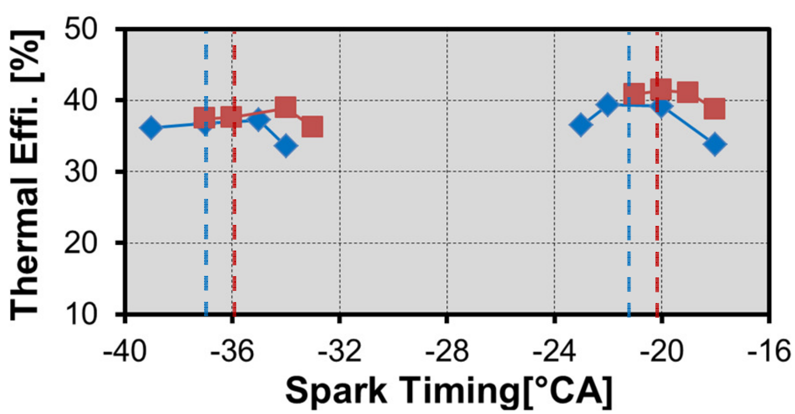
P_{in} = 187kPa

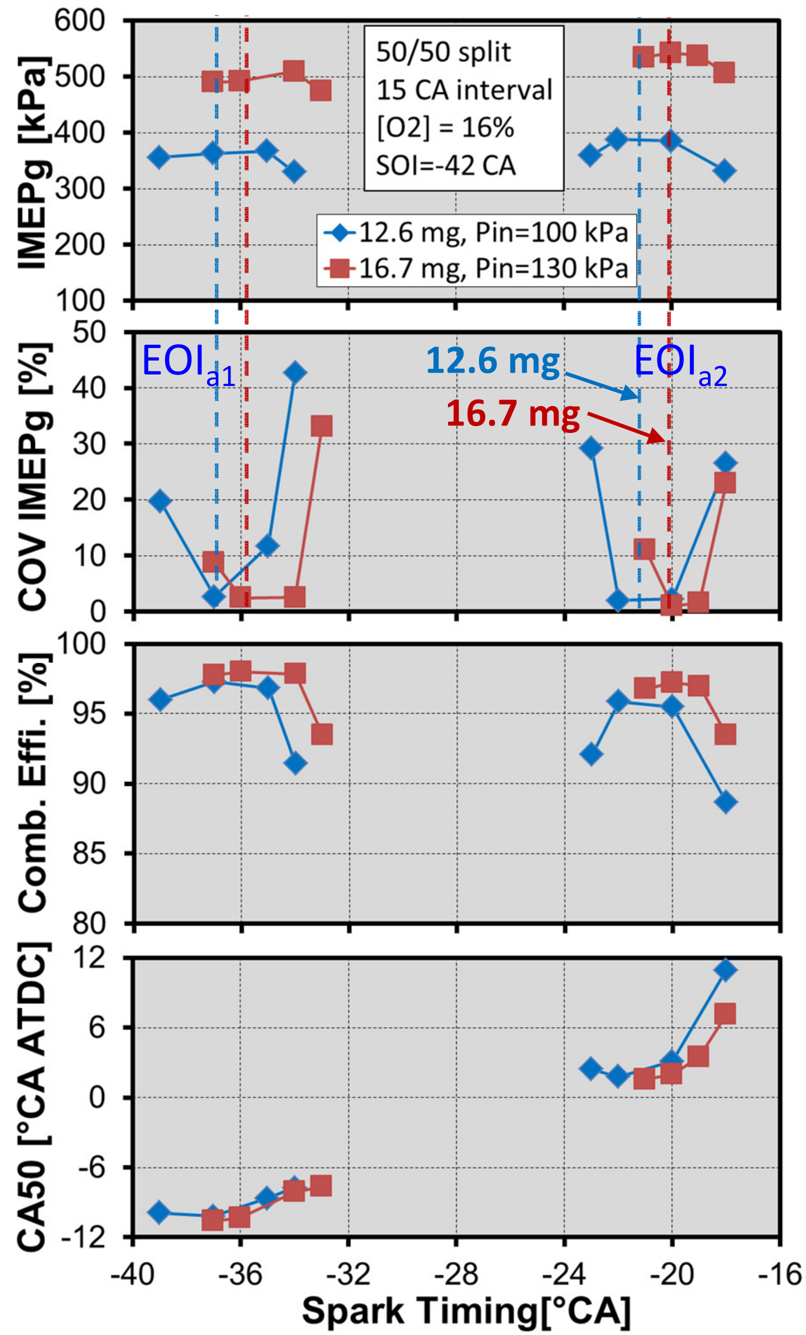


Double Injection – ST Sweeps

- Both igniting 1st and 2nd sprays can lead to stable combustion
- Either igniting 1st or 2nd spray, ST needs to coincide with EOI for stable operation
- Higher CE if igniting 1st spray
- However, igniting 1st spray results in a much earlier CA50 ⇒ Reduced TE

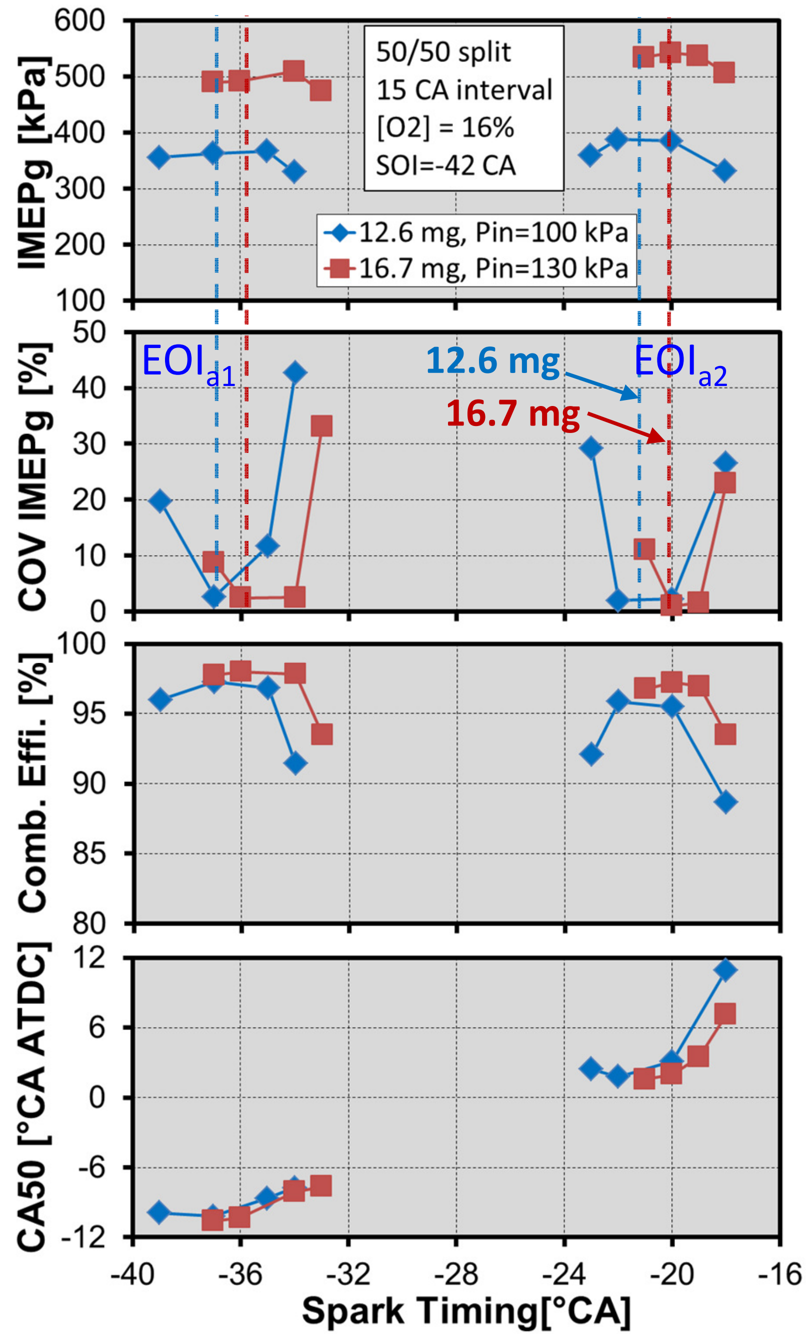


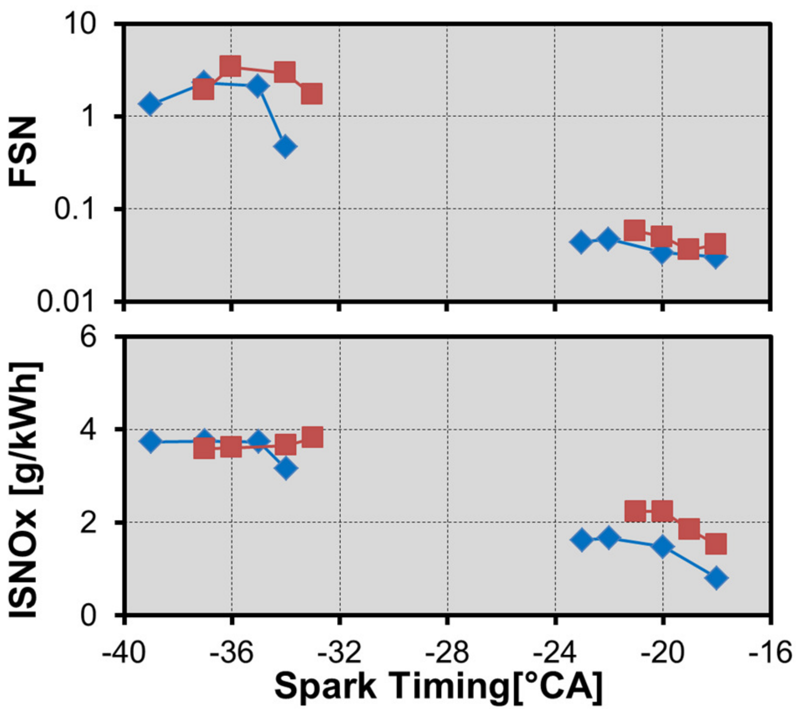




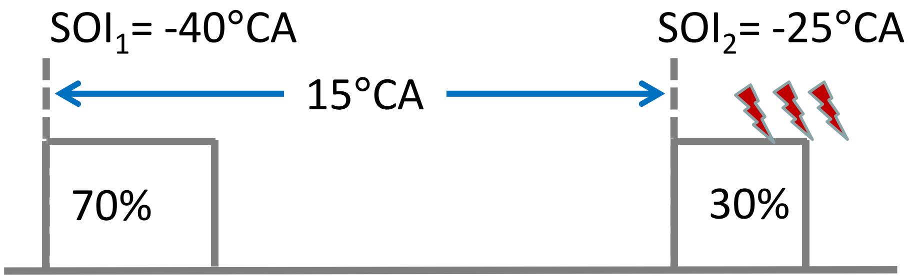
Double Injection – ST Sweeps

- Igniting 1st spray causes extremely high soot emissions.
- Mixing-controlled combustion.

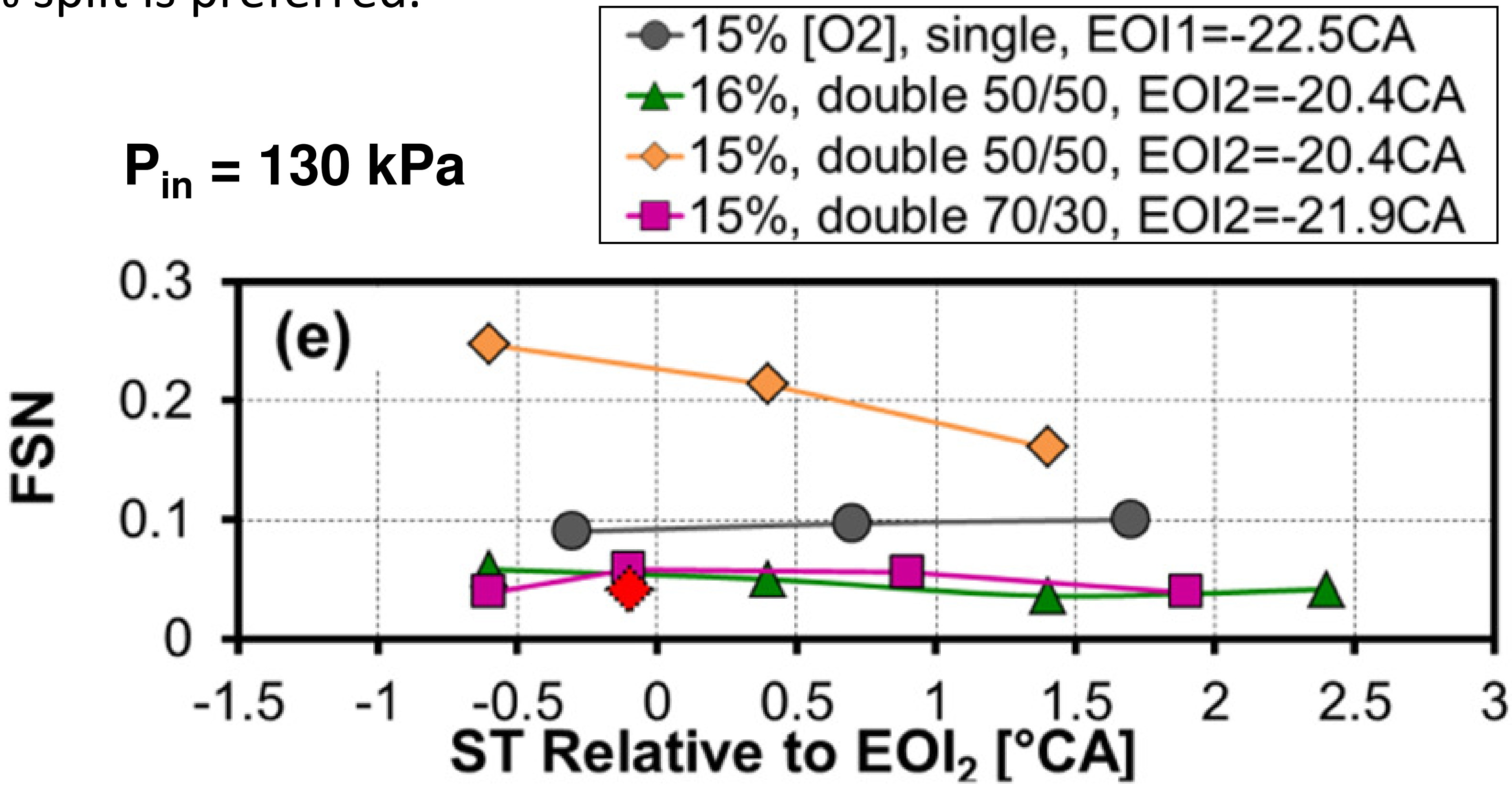




70/30 Split Ratio for Low Smoke

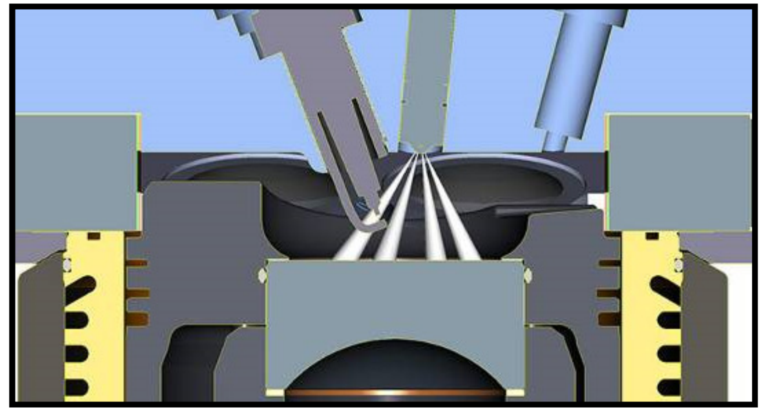


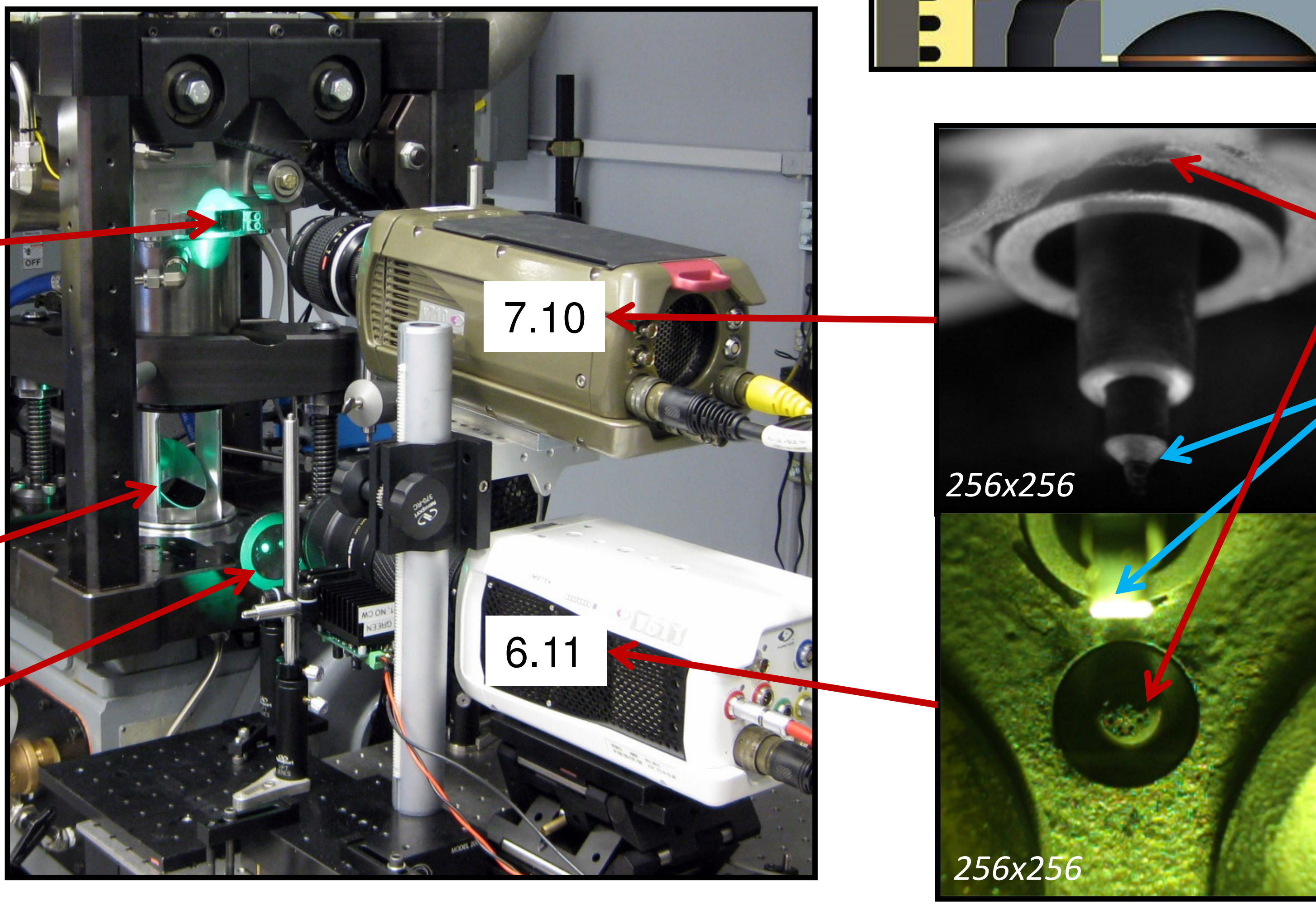
- 50%/50% split stabilizes combustion for $[O_2] < 16\%$.
- But is not optimal from a smoke perspective.
- A 70%/30% split is preferred.



High-Speed Spray Visualization

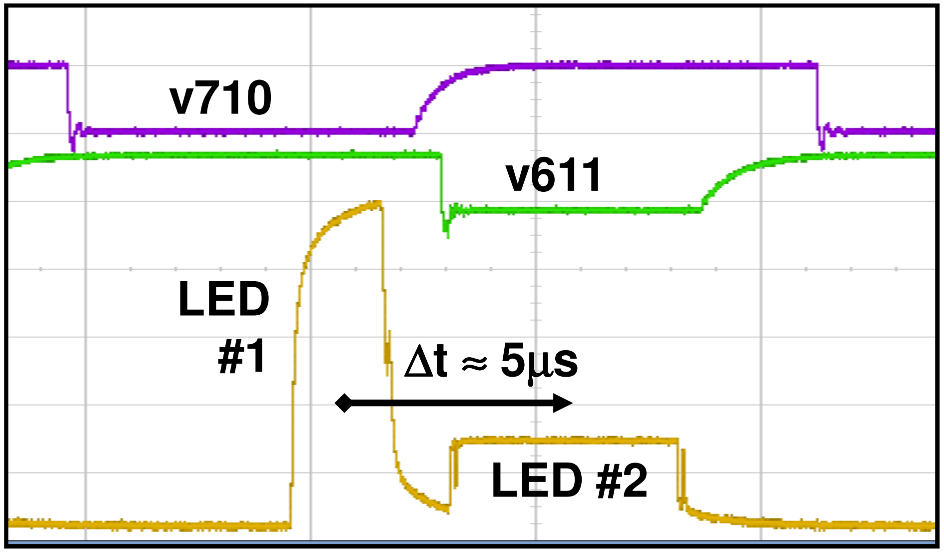
- 60 kHz – 0.1°CA resolution. Dual cameras.
- Requires timings of LED pulses to be offset to avoid reflections.



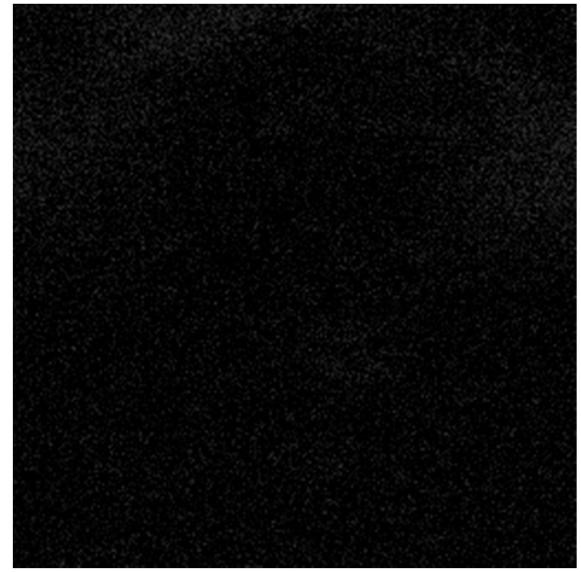


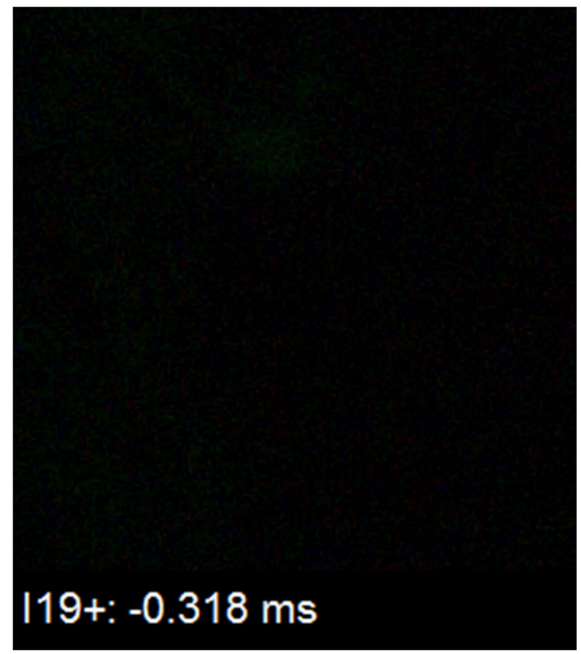
High-Speed Spray Visualization

- Oscilloscope screen dump shows that LED light pulses effectively differ by 5μs.



- Injection pressure = 170 bar. SOI_1 = -40°CA, SOI_1 = -25°CA.
- 70% / 30% split.
- No spray collapse is observed.





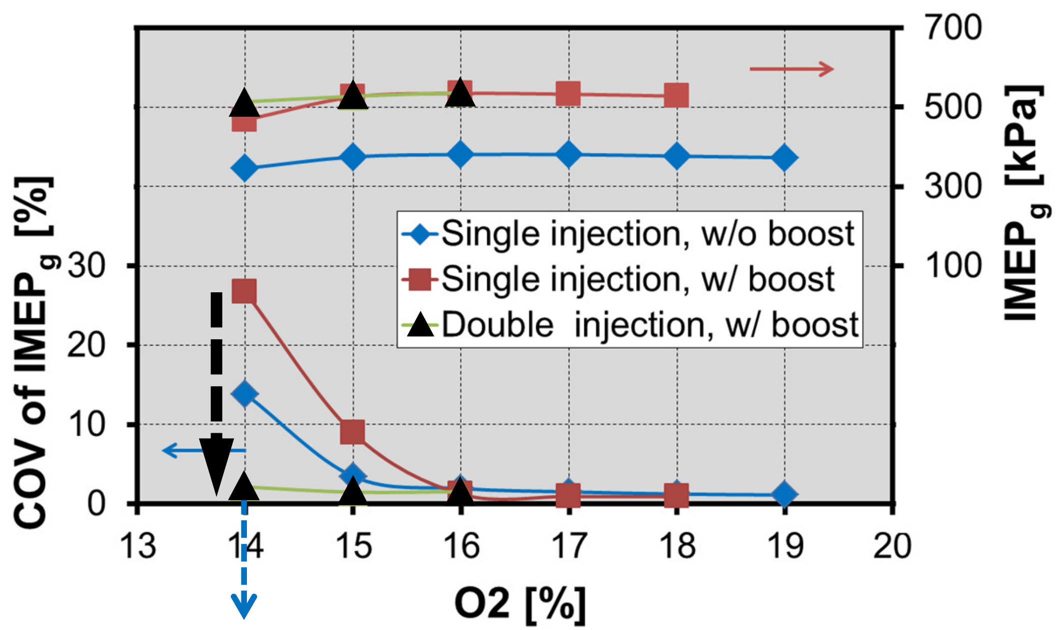
Steps Toward Low NO_x & Soot

EGR → **Slight boost** → **Double-injection** (70/30 split, 15°CA dwell)

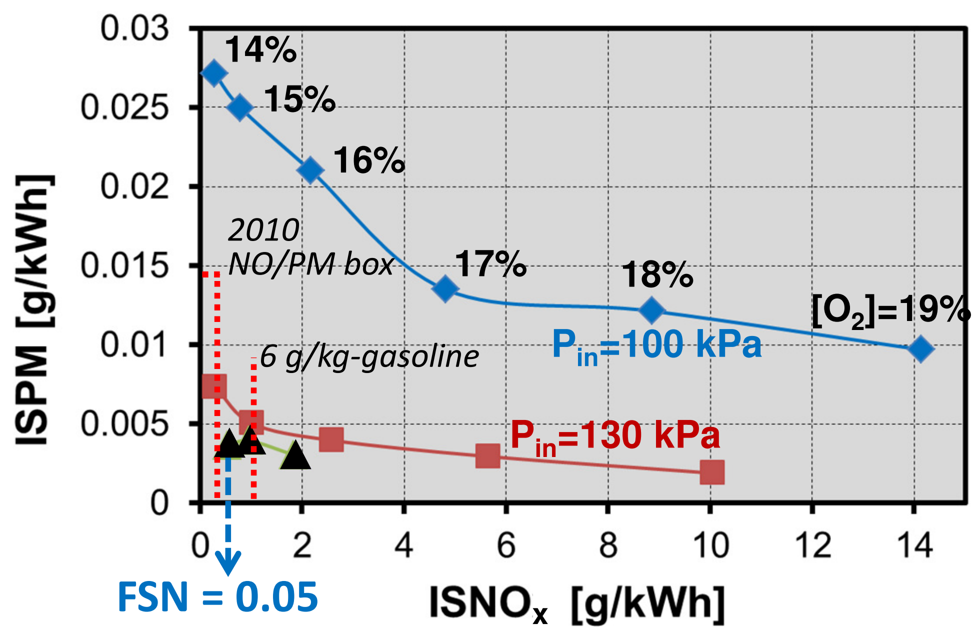
Suppress NO_x, but high Soot

Significant soot reduction due to less wall-wetting, but high COV

Optical study: why is double injection better for low NO_x operation?



TE=39.4%, COV=2.2%



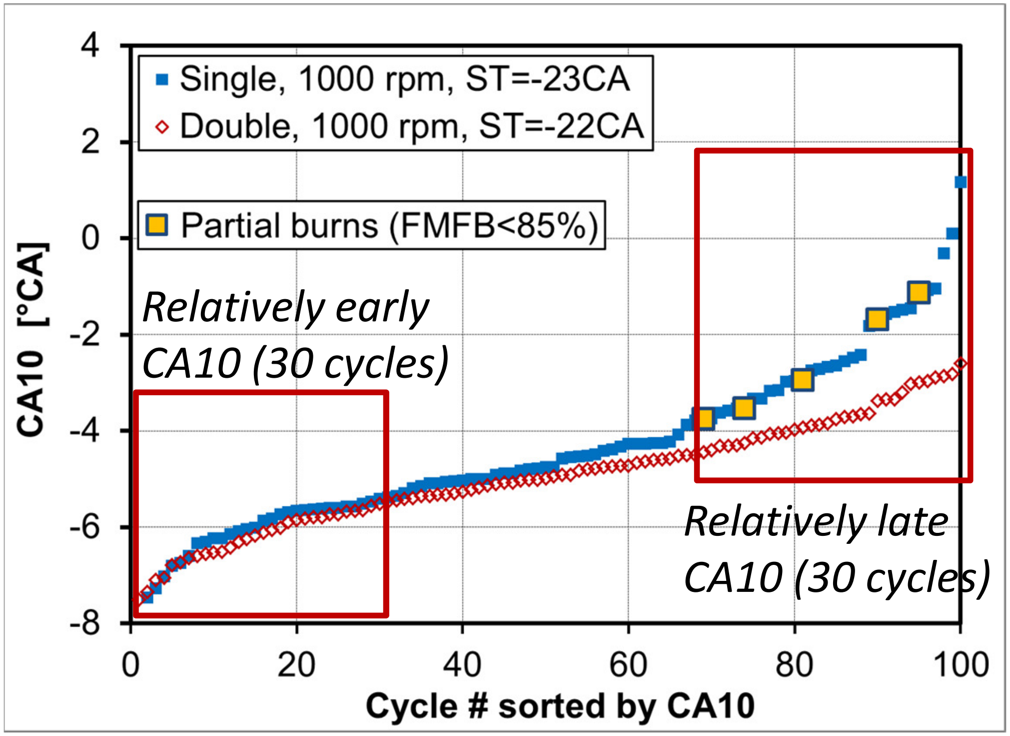
FSN = 0.05

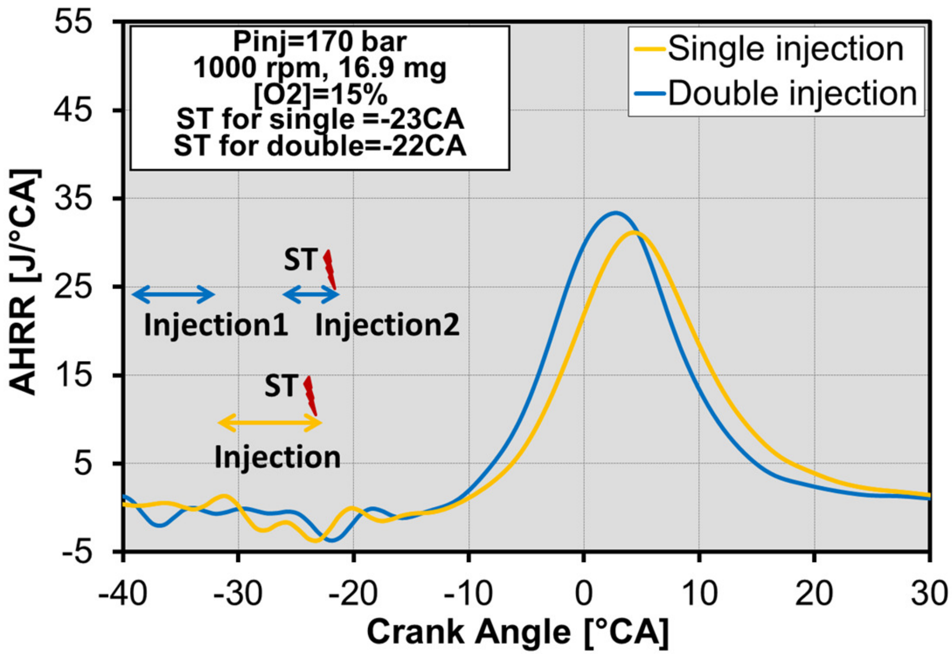
NO_x = 43 ppm

NO_x = 2.53 g/kg-gasoline

High-Speed Imaging Statistics

- P_{in} = 130 kPa, $[O_2]$ = 15%.
- Double injection avoids late-CA10 cycles that develop into partial burns.

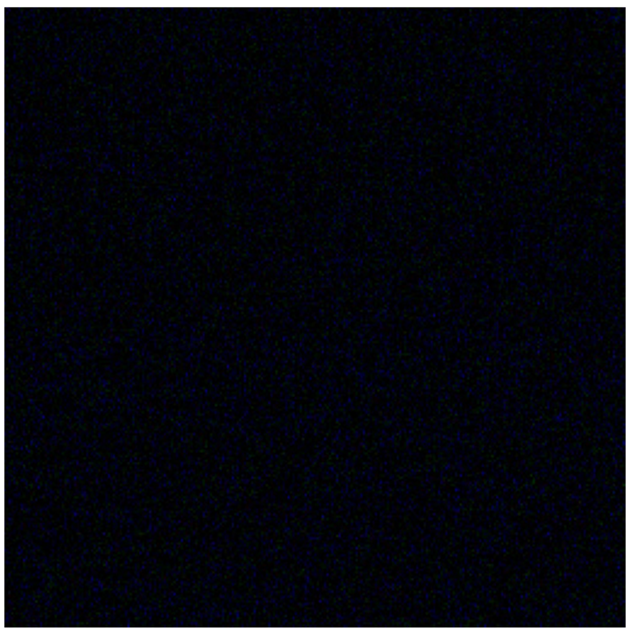


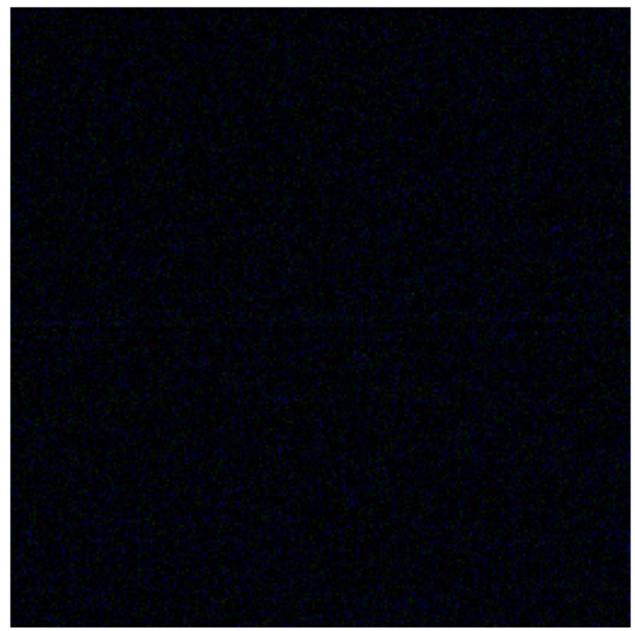


High-Speed Imaging – Single vs. Double

- Individual cycles selected statistically to represent late CA10.

Single | ***Double***





High-Speed Images – Single vs. Double

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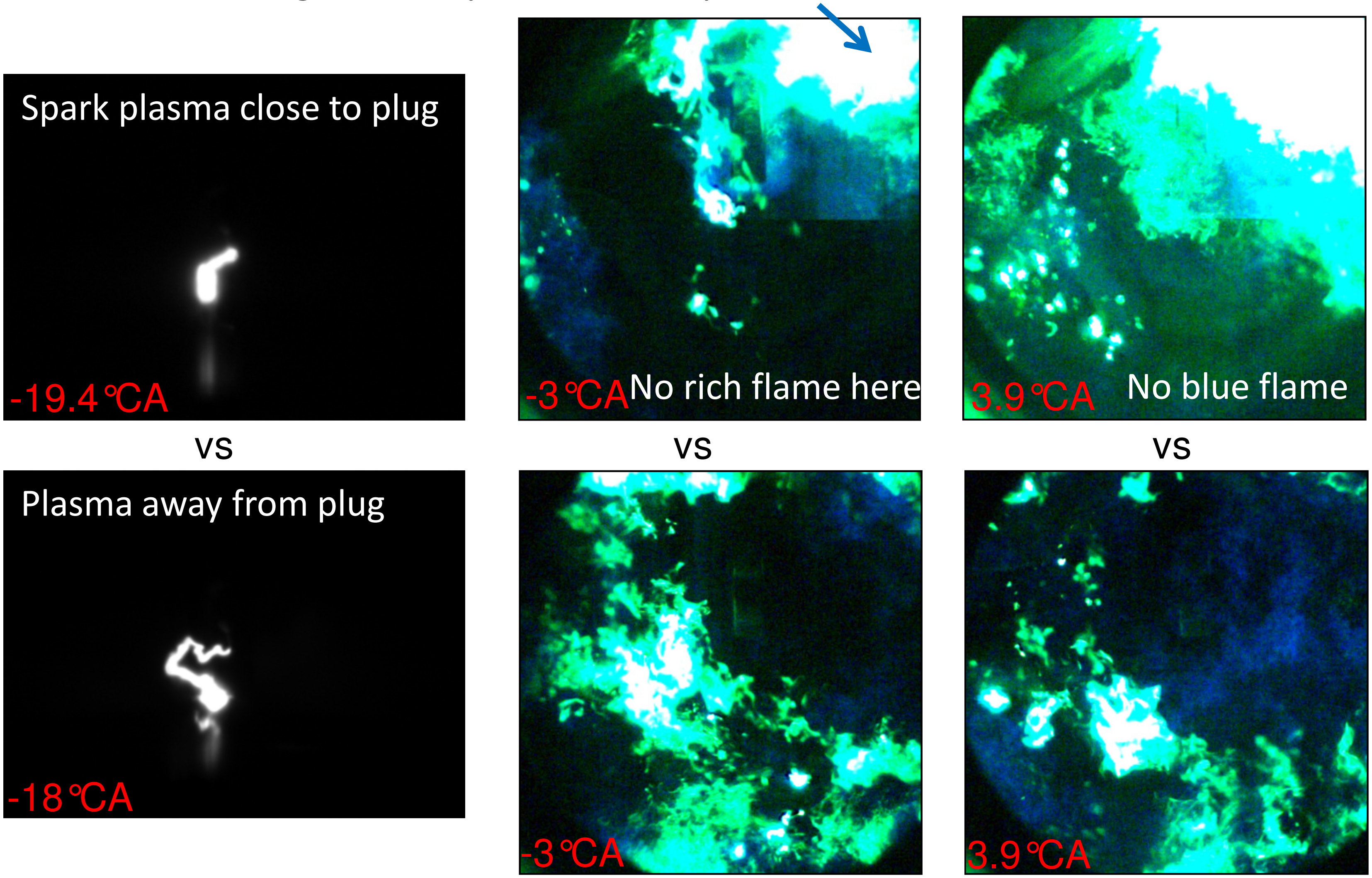
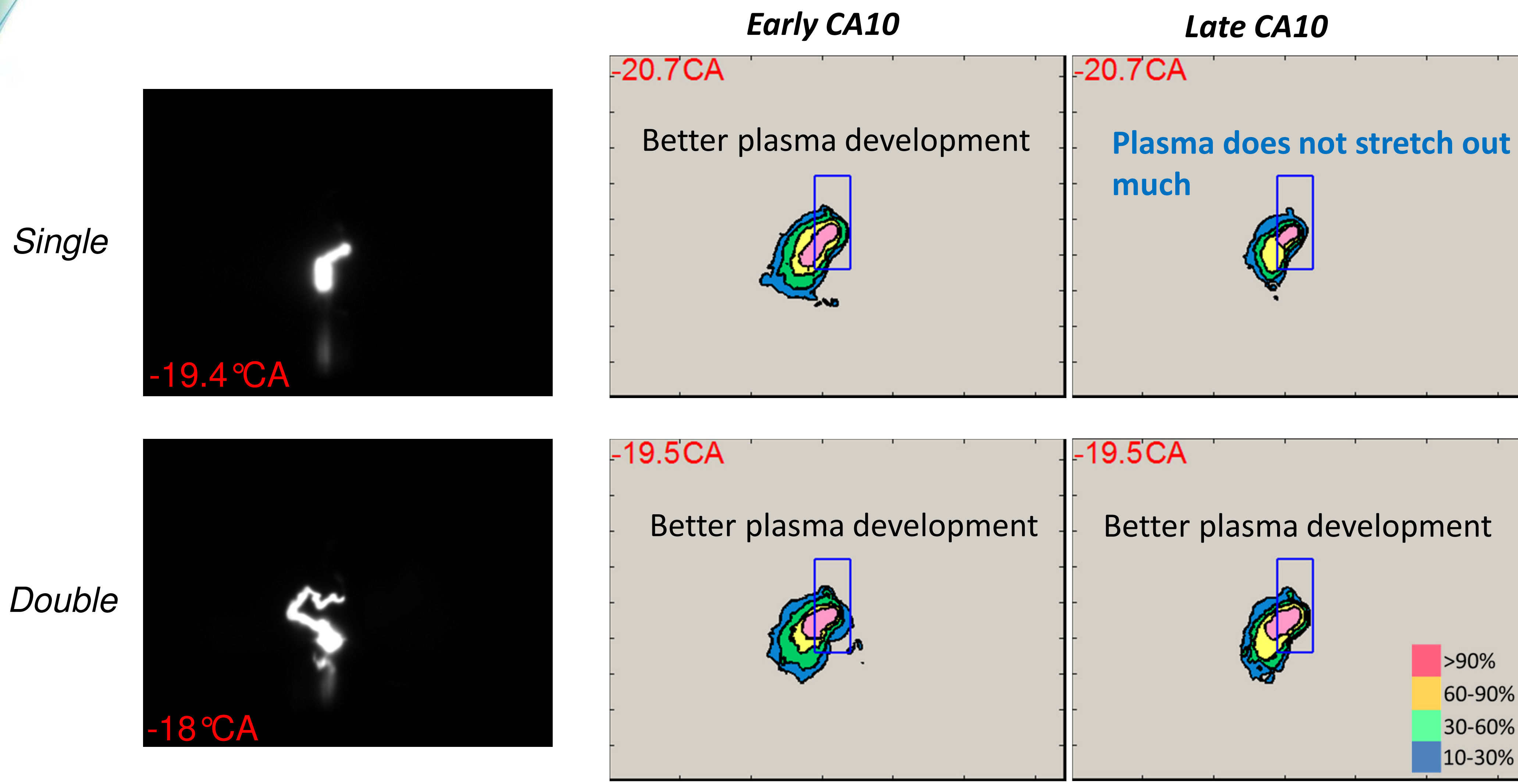


Plasma Stretch – Conditional Analysis

- Spark motion -> early combustion

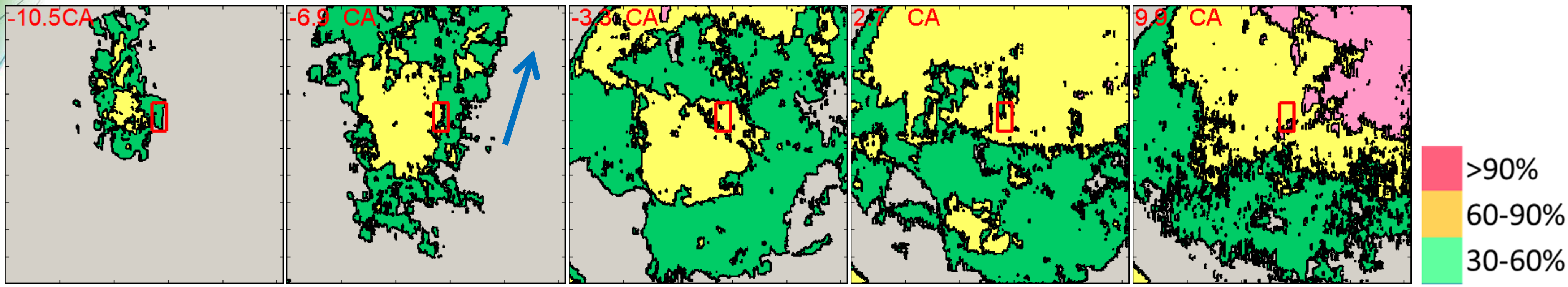


This indicates that double injections increase the probability of pushing the plasma away from the spark plug.

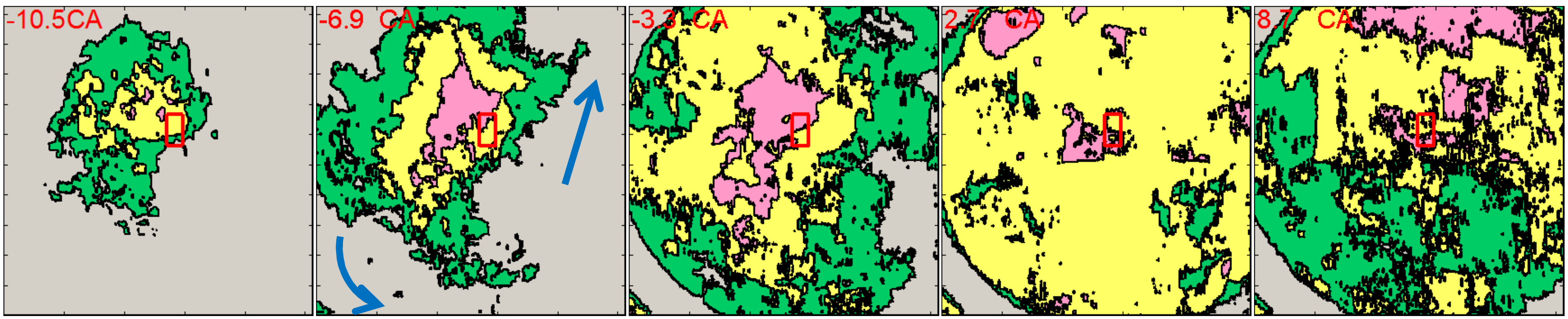
Flame Propagation After CA10

Flame travel towards 12 o'clock direction and stays in the vicinity of upper-right corner.

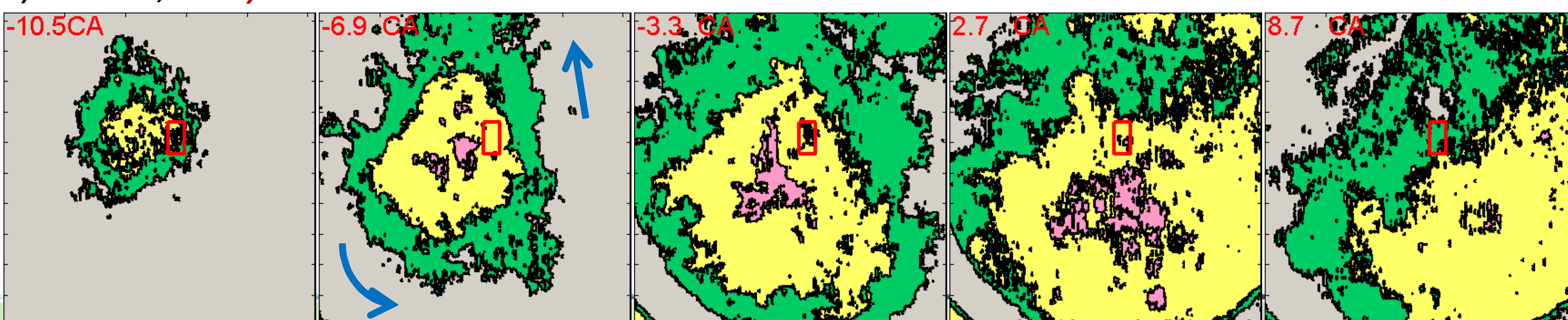
1) Single, late CA10, FMFB<90%



2) Single, early CA10, FMFB>92%

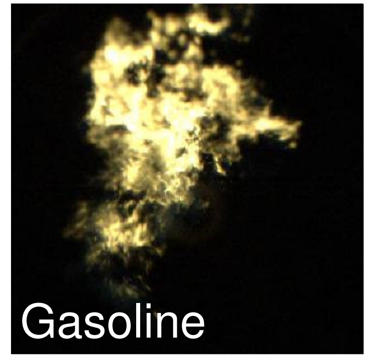


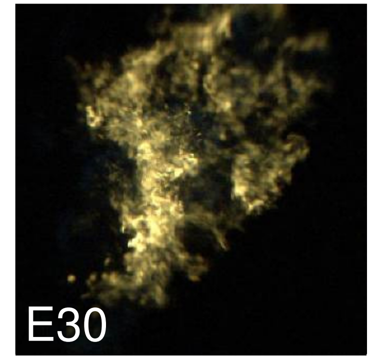
3) Double, no cycle has FMFB <92%

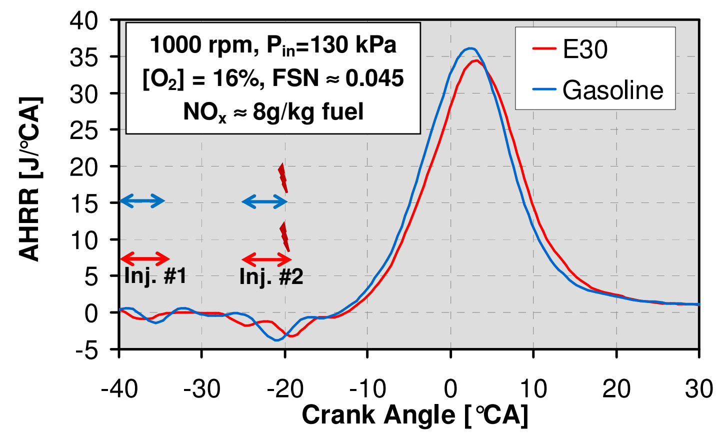


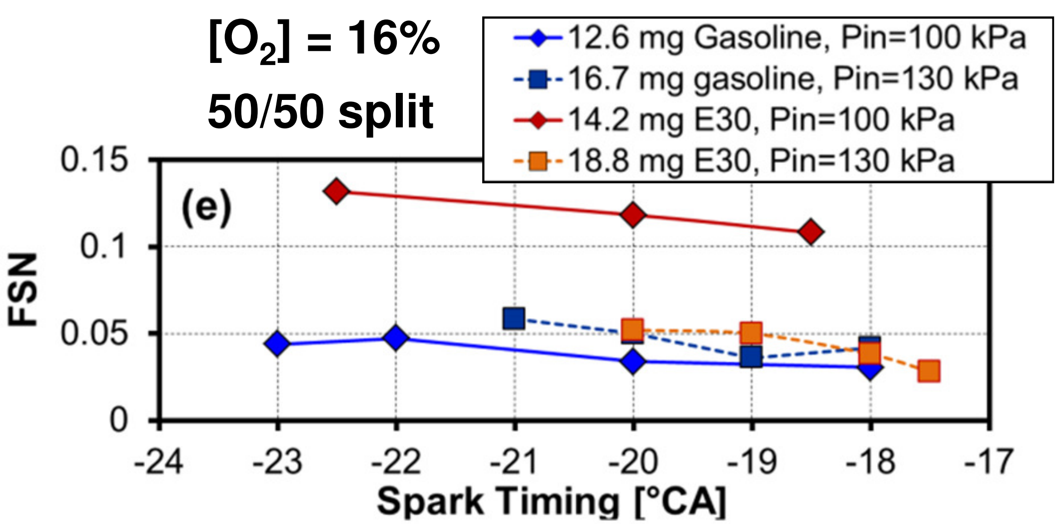
Boosted Stratified Operation with E30 & Gasoline

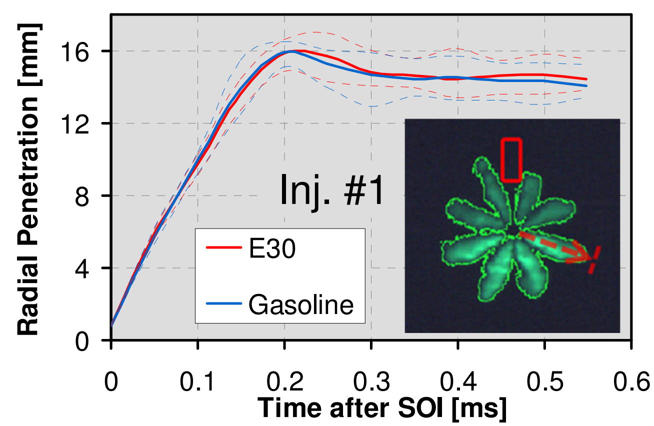
- Does E30 pose challenges here?
- Results indicate similar characteristics:
  - Liquid spray penetration.
  - Heat-release rate.
  - Combustion stability for low NO_x operation.
  - Flame-spread patterns.
- However, for P_{in} = 100 kPa, E30 shows higher smoke.
  - Wall wetting?











Summary

- Moderate boost can extend the load range of highly efficient stratified-charge SI operation.
- For single injection, boost can strongly suppress soot emissions but combustion instability can arise for low-NO_x operation.
- Using <u>double injection</u> with a 70/30 split enables stable combustion with low smoke (FSN<0.05) and NO_x (43 ppm).
- In most aspects, E0 - E30 fuel blends are equally compatible with highly efficient stratified-charge SI operation.
- Only area of concern is elevated soot emissions for non-boosted operation with E30 at 1000 rpm.

Acknowledgements

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U.S. DEPARTMENT OF ENERGY

Co-Optimization of Fuels & Engines

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