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Combined Effects of Gasoline Composition and Operating Strategies on Soot-Production Pathways for Stratified-Charge SI Operation

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Co-Optimization of Fuels & Engines

Abstract

Increased engine efficiency is essential for complying with ever stringent fuel-economy standards. Lean unthrottled stratified-charge engine operation can offer large efficiency improvements compared to stoichiometric operation. However, due to the cost and complexity of lean-NO_x aftertreatment, it is imperative to maintain low engine-out NO_x via the use of EGR.

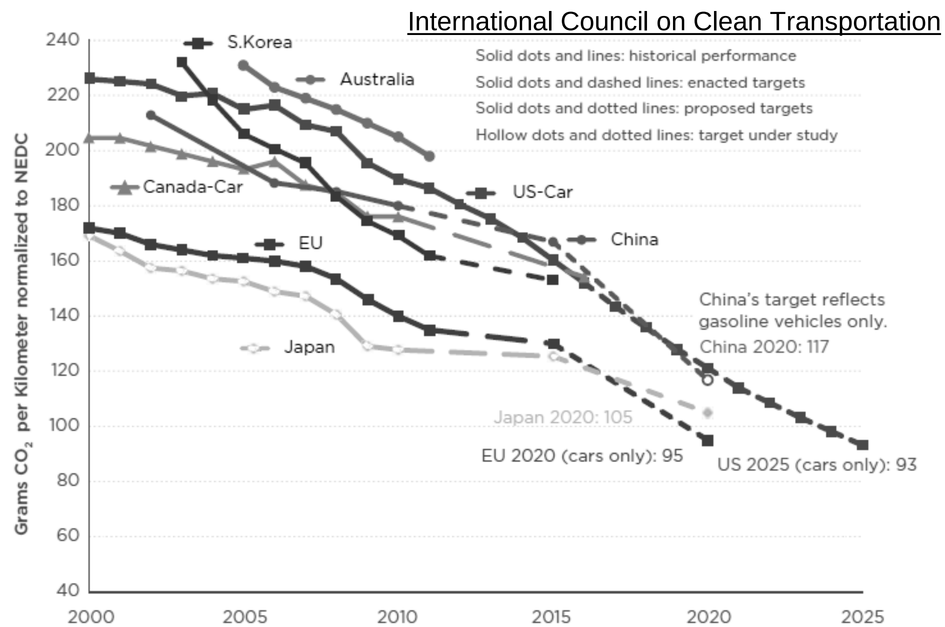
Engine testing for various combinations of fuels and operating conditions reveal that the NO_x / PM trade-offs vary widely, suggesting that the dominating pathway to engine-out soot vary as well. Various optical diagnostics are applied to determine for what combinations of fuels and operating conditions wall-wetting of the piston bowl occurs. Specifically, a variant of an refractive index matching (RIM) technique is implemented to quantify the fuel-film area as a function of crank angle. Three gasoline-like Co-Optima Core Fuels are investigated; alkylate, E30 and high-aromatics gasoline.

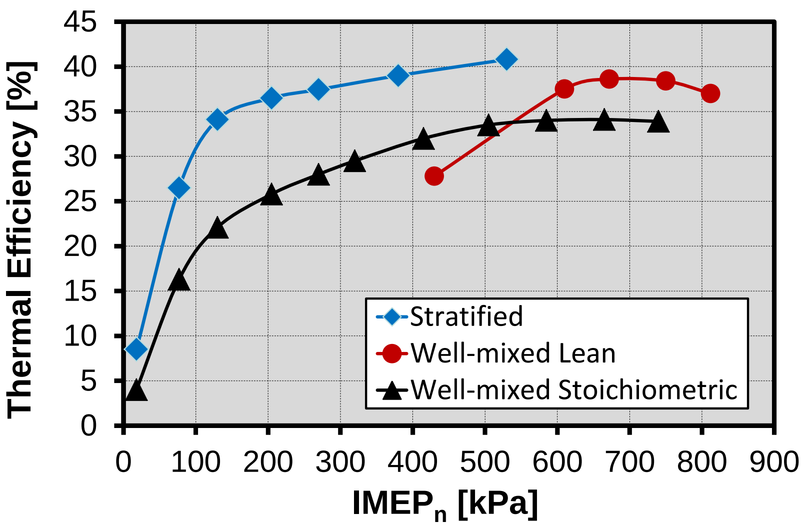
It is found that the effect of fuel type is very strong for stratified-charge SI operation, and this needs to be carefully addressed when a new fuel is developed for market introduction, especially with new bio-based molecules. Propensity for a fuel to generate smoke is addressed by identifying soot-formation pathways. The current work identifies two; Wall-affected soot formation (*aka* pool-fires), and bulk-gas soot formation. Pool-fires are promoted by low P_{in}, high $[O_2]$ and low coolant temperature. E30 fuel have worst smoke emissions for such wall-affected soot formation, and this suggests that vaporization properties have higher importance than chemical composition.

Bulk-gas soot formation is the dominating pathway for boosted operation at 2000 rpm. Here, the high-aromatics fuel have the worst smoke emission since fuel chemistry dominates over physical properties. The alkylate fuel shows superiorly low smoke for all conditions, consistent with its lack of aromatics and having a low end-boiling point.

Introduction

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

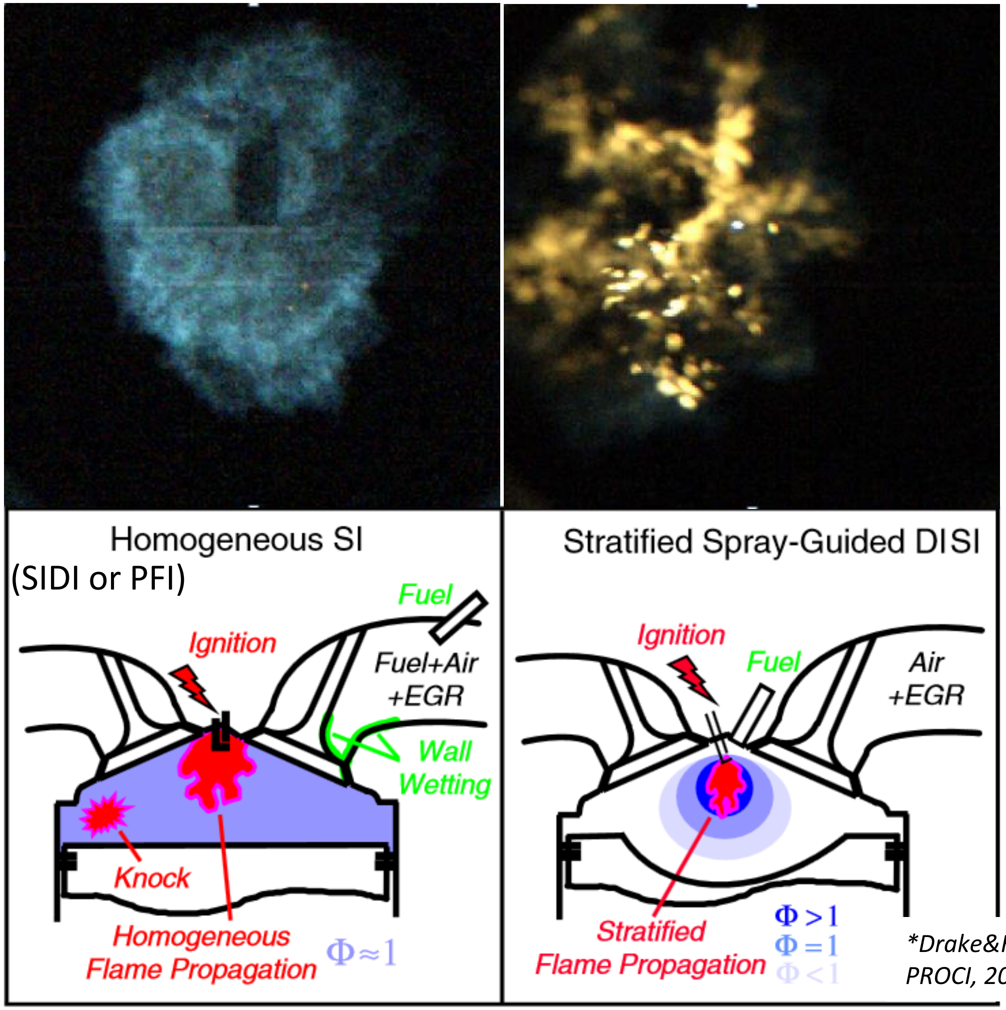




- Lean operation may well be required for SI engines to meet CO_2 requirements.
- Stratified-charge operation has a strong efficiency potential.

Co-Optima Thrust 1 Efforts

- Co-Optima Thrust 1 efforts are investigating the potential of a new high-octane gasoline with new biofuels content.
- High octane benefits knock-limited operation.
- A new fuel should preferably be well compatible with stratified-charge SI operation.
- A specific concern is the sooting propensity.

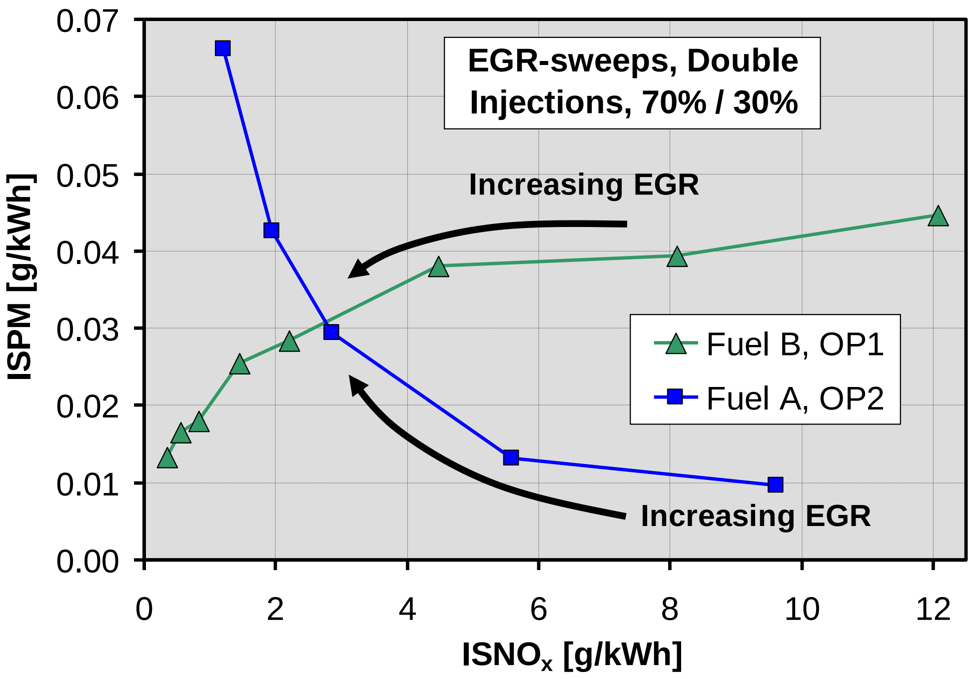


**Drake&Haworth PROCI, 2007*

Throttled flow rate control	Un-throttled load control
well-mixed stoichiometric	overall-lean
(Knock, pumping loss)	(Soot, NO_x, CCV)

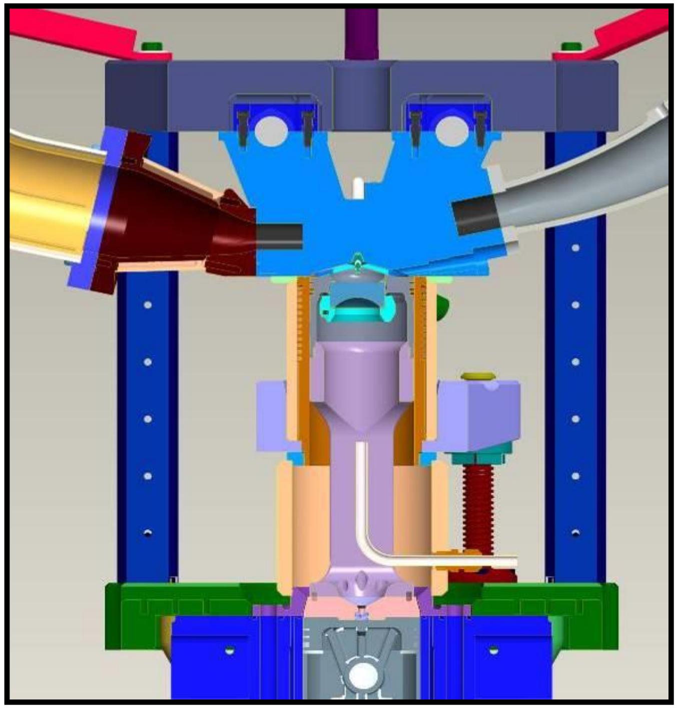
PM / NO_x Trade-Off Examples

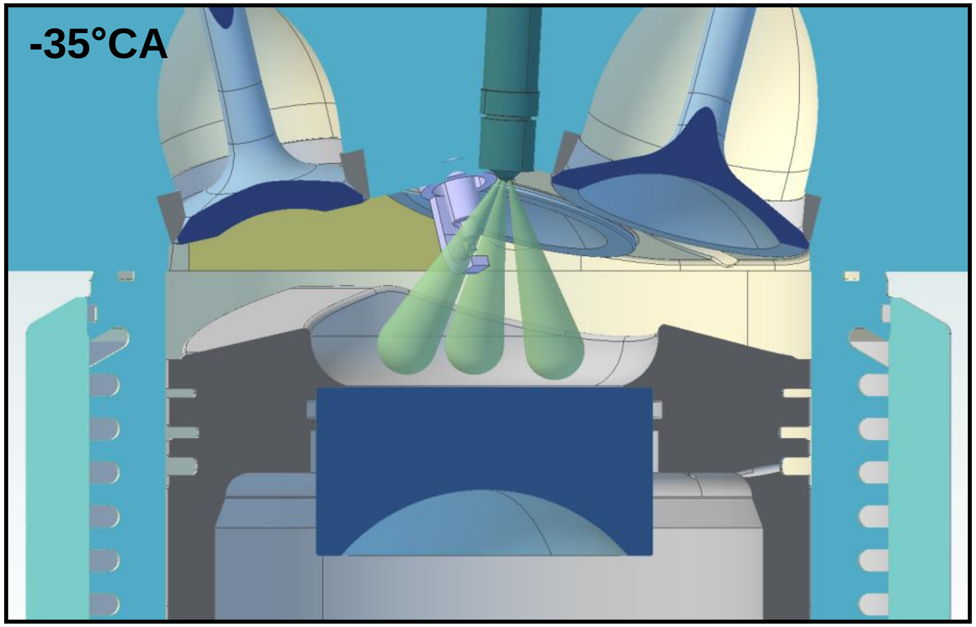
- Lean NO_x aftertreatment is a challenge. Therefore, EGR must be applied to maintain "reasonable" engine-out NO_x.
- Depending on fuels and operating point, the application of EGR can lead to either increasing or decreasing smoke!
- Engine out soot = (Soot formed) – (soot oxidized)
- Soot oxidation will generally be impeded by EGR.
- The soot formation mechanisms / pathways appears to be very different for these two examples.

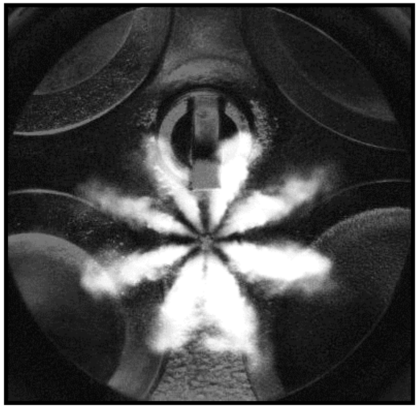


Research Engine

- 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.**

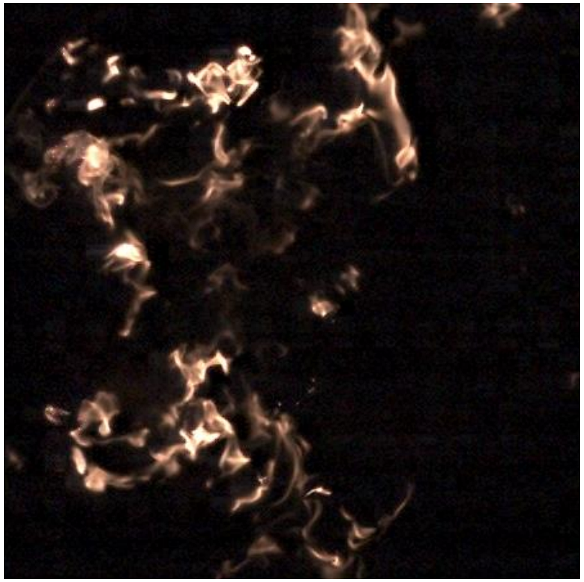




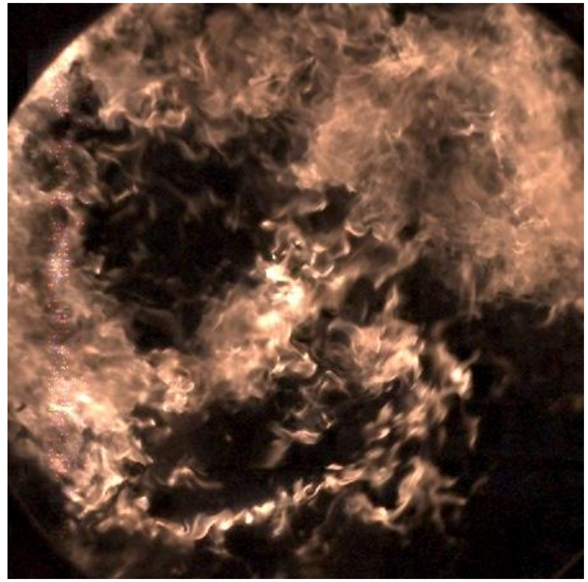


High-speed Imaging of E85

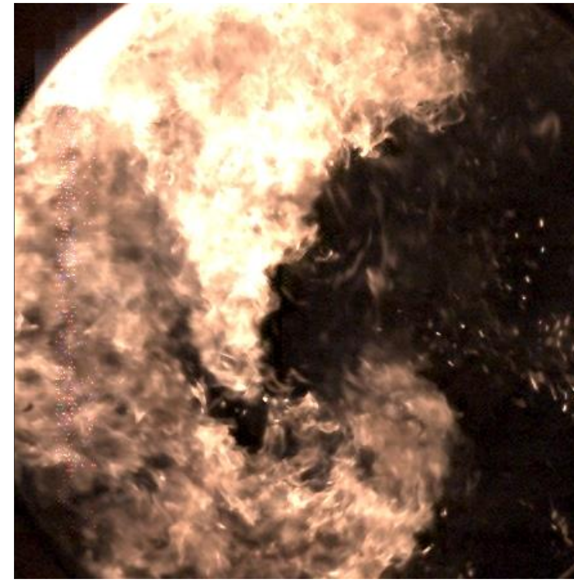
- Cycles selected to show representative luminosity histories.



ϕ = 0.08, 5.6 mg

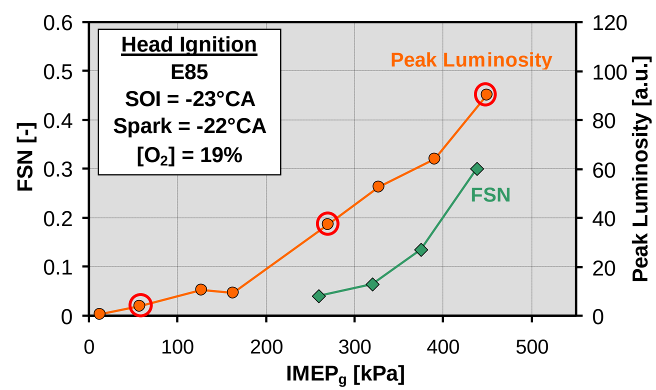


ϕ = 0.20, 14 mg



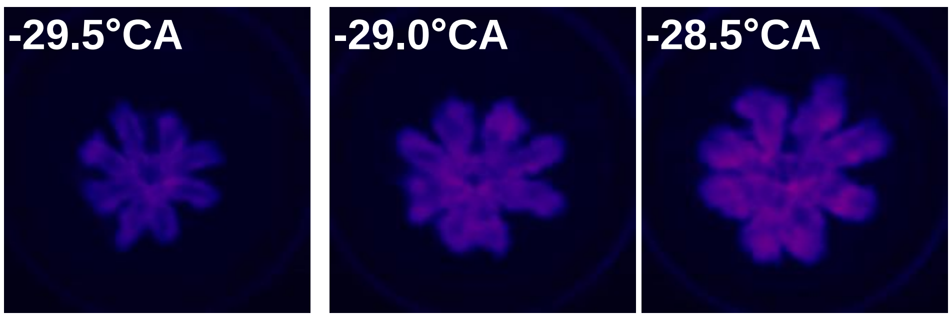
ϕ = 0.32, 22 mg

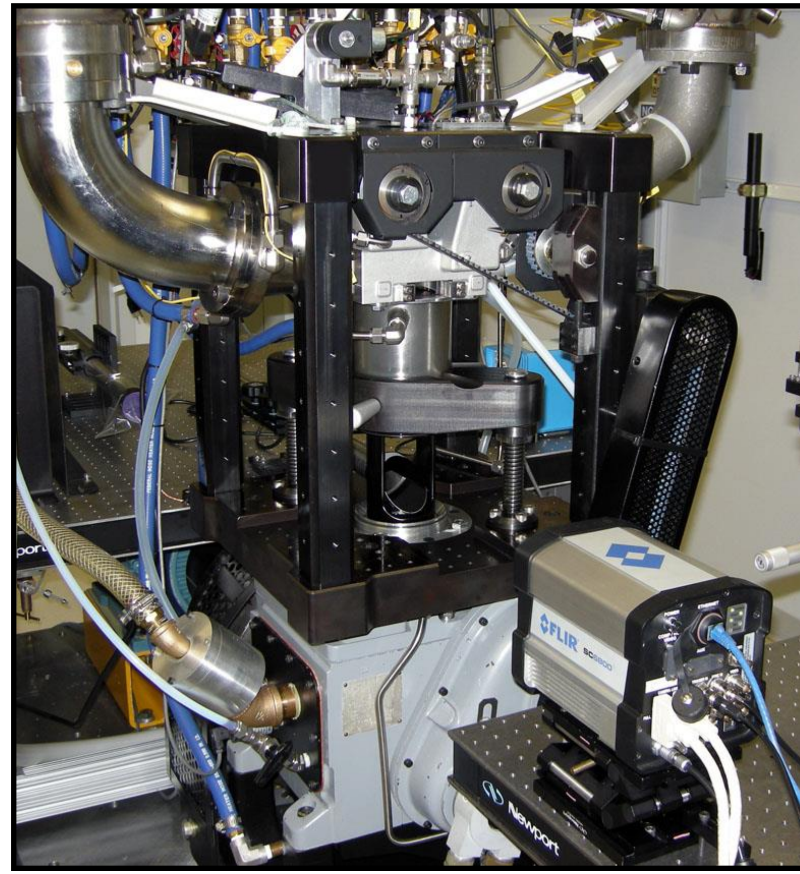
- 20 kHz movies, played at 20 frames/s.
- More bulk-gas soot at higher load.
- Increasing flow velocities at higher load.
  - More injected fuel momentum.
- Highest load shows flame patterns indicative of pool fires.



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.

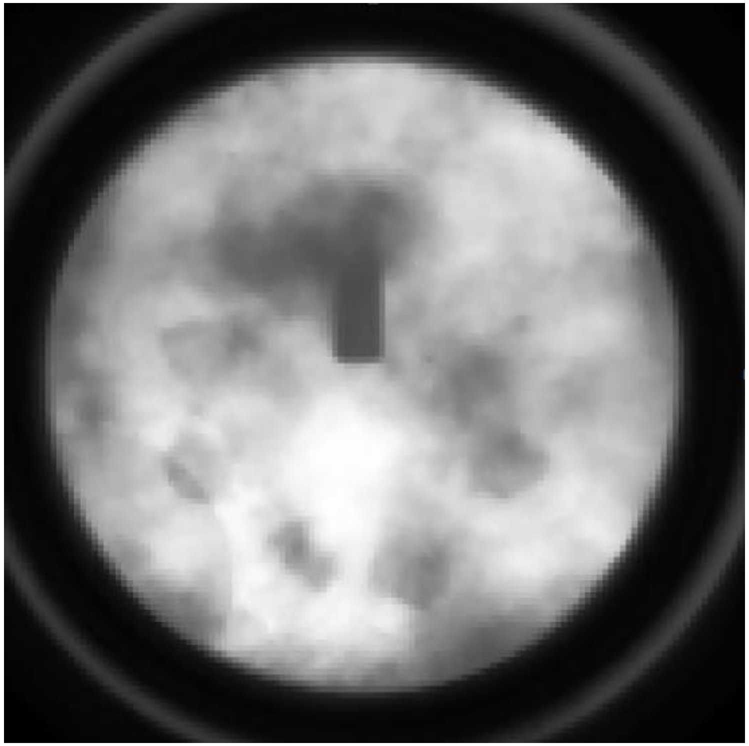




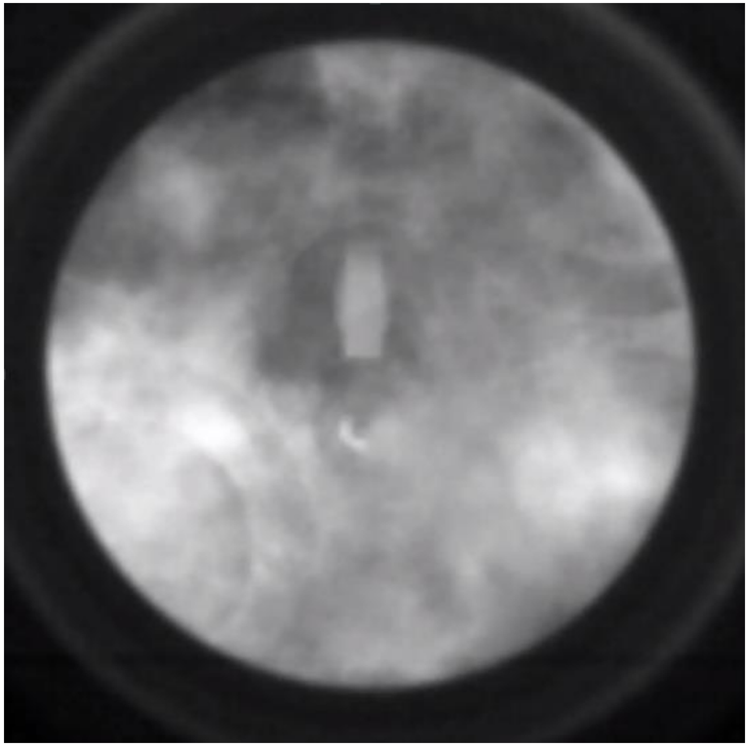
Effect of Injection Amount on Wall-Wetting

1000 rpm, P_{in} = 98 kPa, E85, SOI = -23°CA, No Swirl

13 mg

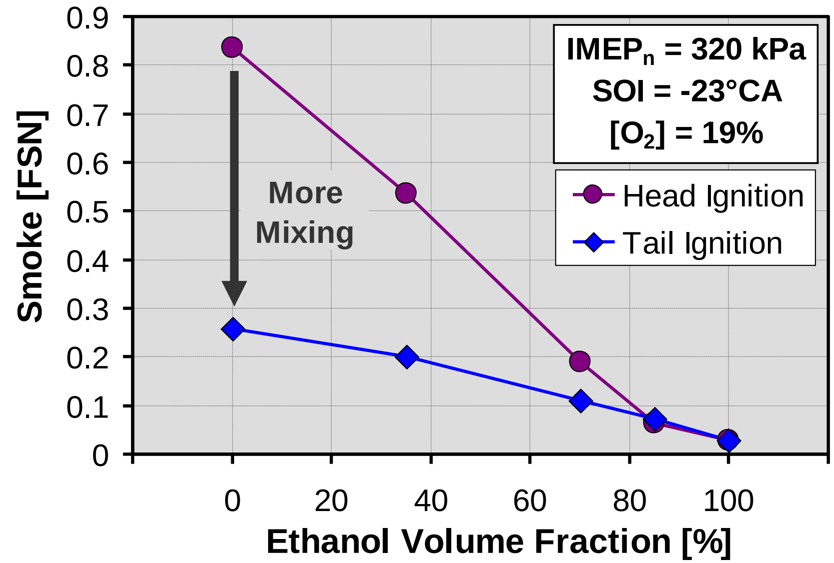


3.6 mg



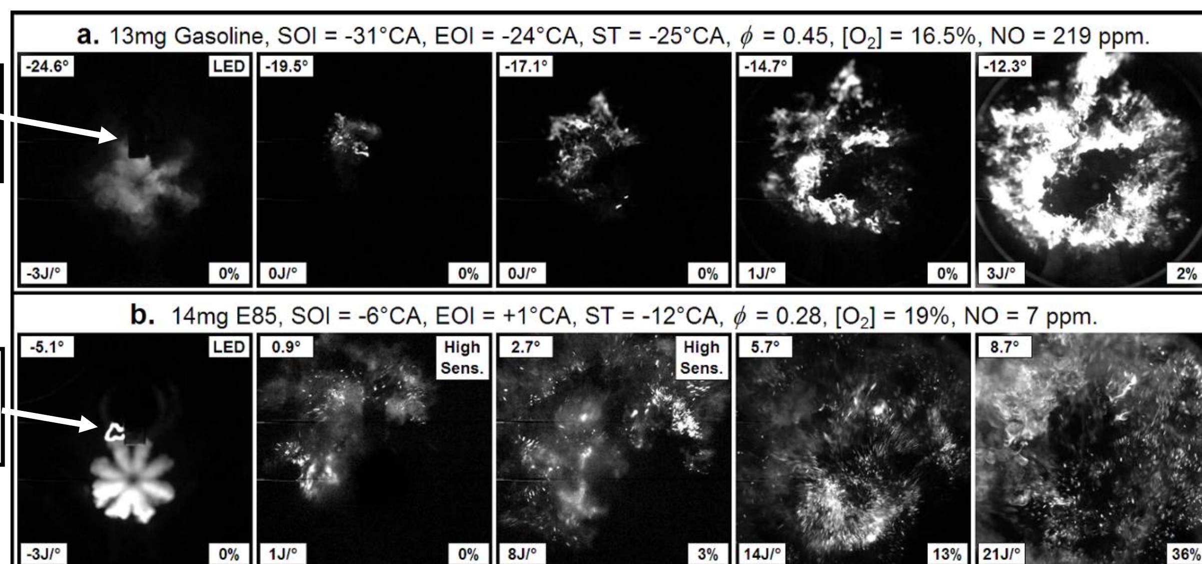
Smoke vs. Fuel Type & Ignition Strategy

- Sooting tendency generally decreases with more ethanol.
  - Oxygenated fuel & strong vaporization cooling suppresses rich combustion.
- Highly stratified operation is not suitable for gasoline.
  - Smoke mandates tail ignition.



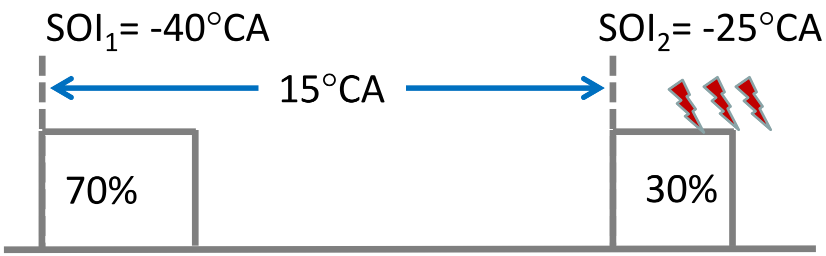
Gasoline Tail Ignition

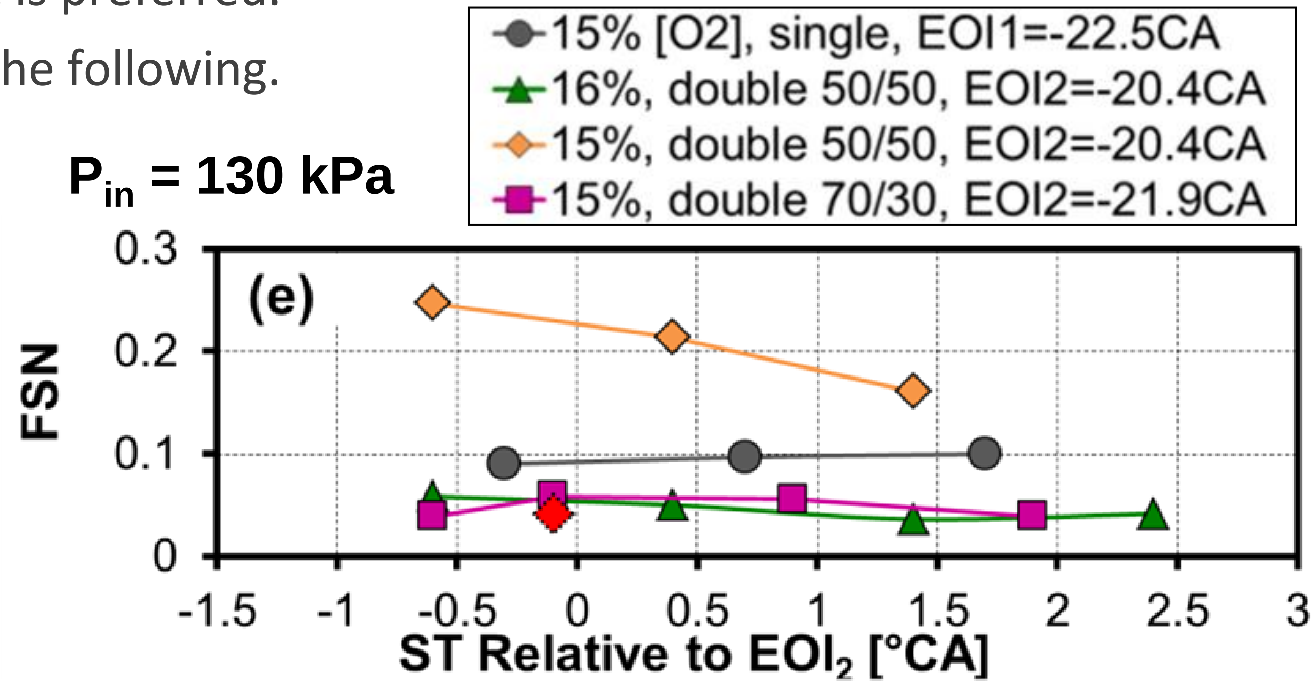
E85 Head Ignition



70/30 Split Ratio for Low Smoke

- A previous study shows that single injection can result in misfires for boosted operation.
- 50%/50% split stabilizes boosted operation for $[O_2] < 16\%$.
- But is not optimal for smoke.
- A 70%/30% split is preferred.
- Will be used in the following.

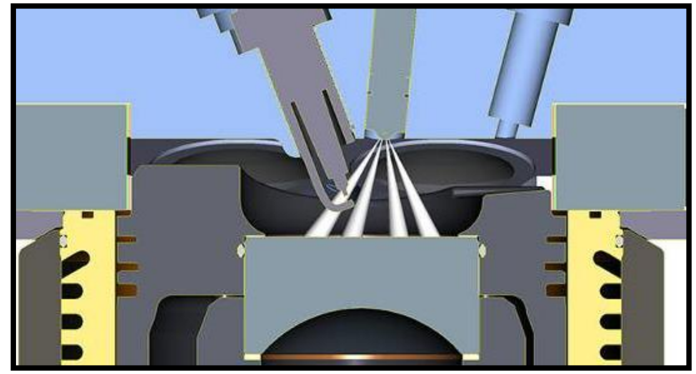


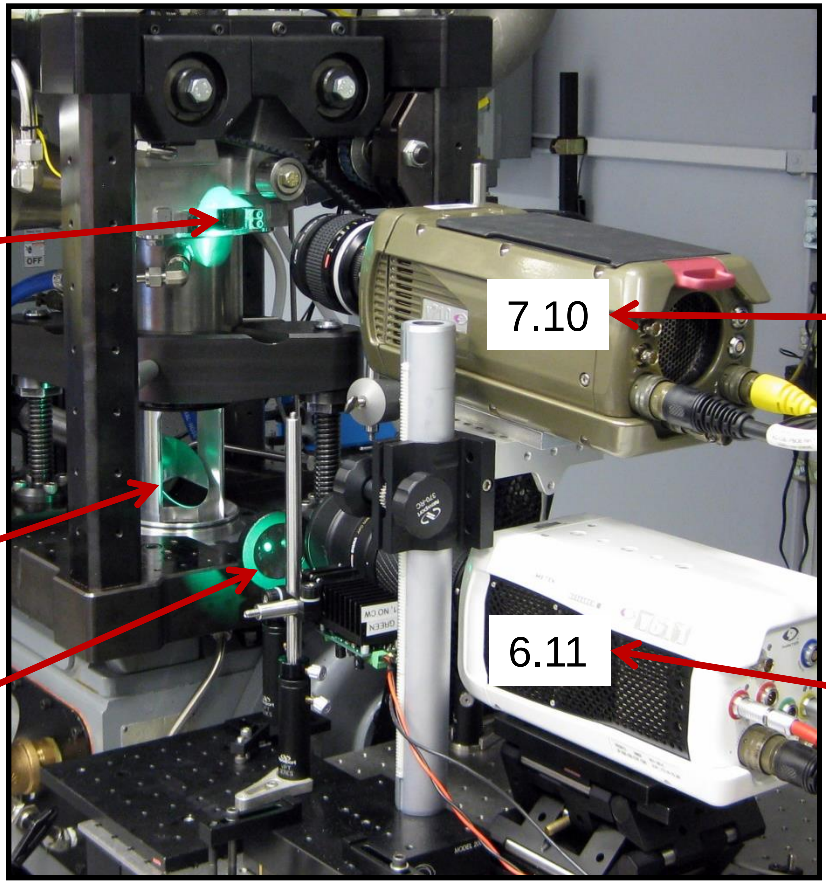


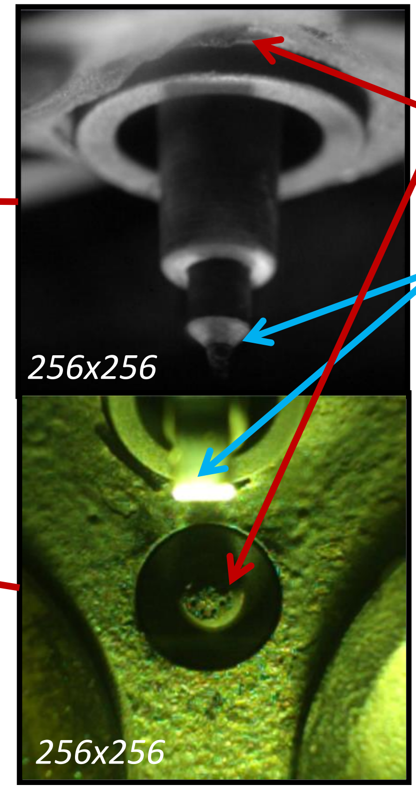
W. Zeng, M. Sjöberg, "Utilizing boost and double injections for enhanced stratified-charge direct-injection spark-ignition engine operation with gasoline and E30 fuels", International Journal of Engine Research, 2017.

High-Speed Spray Visualization

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

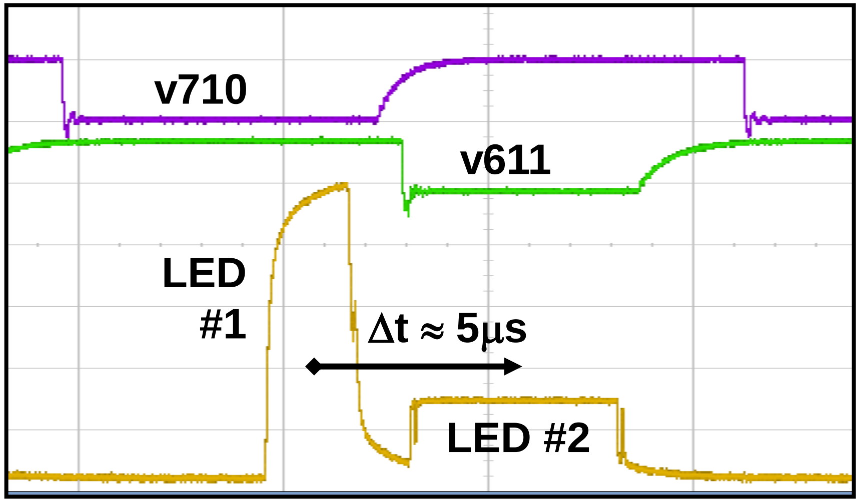




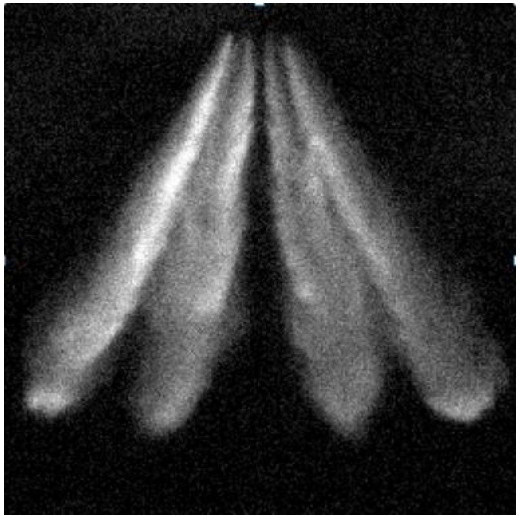


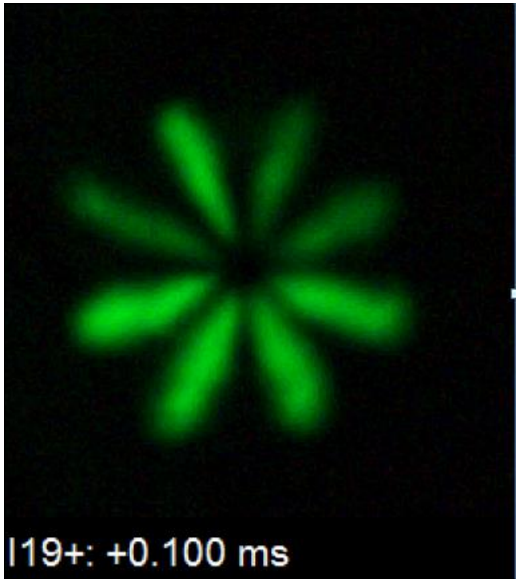
High-Speed Spray Visualization

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



- Injection pressure = 170 bar. SOI_1 = -40°CA, SOI_2 = -25°CA.
- 70% / 30% split.
- No spray collapse is observed.



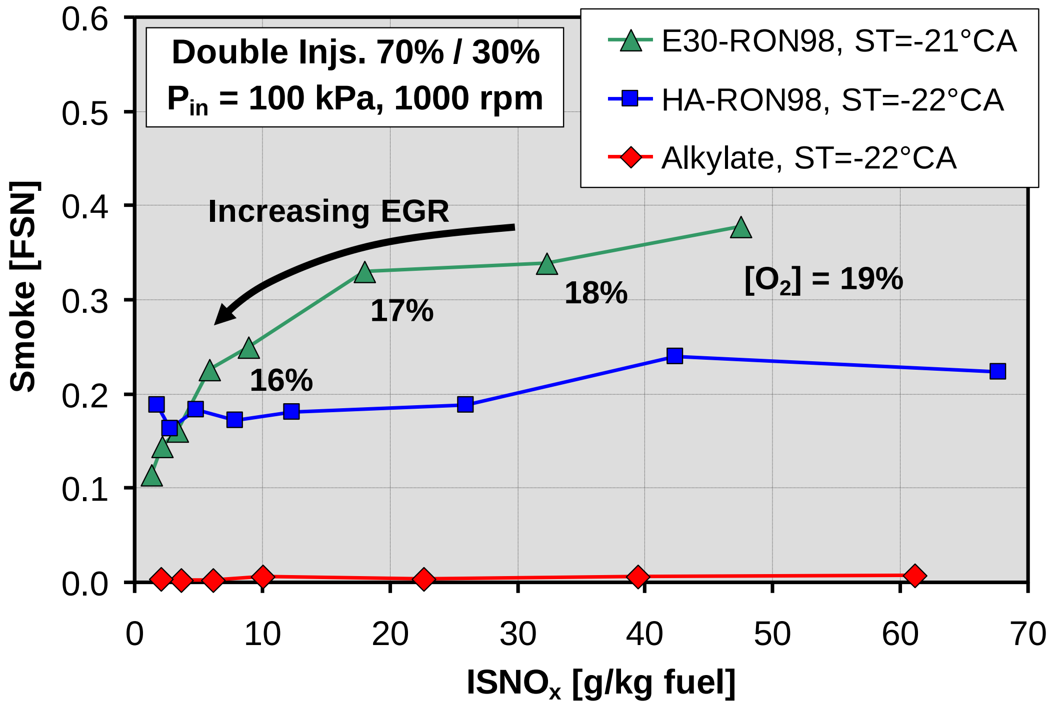


Properties of Co-Optima Core Fuels

	Alkylate	*E30*	*High Aromatic*
RON	98	98	98
MON	97	88	87
AKI (R+M)/2	97	93	93
Sensitivity (RON - MON)	1	10	11
T10 (°C)	93	61	59
T50 (°C)	100	74	108
T90 (°C)	106	155	158
TF (°C)	161	204	204
Aromatics (Vol. %)	0	8	31
Olefins (Vol. %)	0	5	4
Parafins (Vol. %)	100	57	65
Ethanol (Vol. %)	0	30	0
Net Heat of Combustion (MJ/kg)	44.5	38.2	43.0
Average Molecular Formula	C: 7.76 H: 17.45	C: 4.49 H: 9.87 O: 0.5	C: 6.92 H: 12.41

Lower Speed, non-Boosted Operation

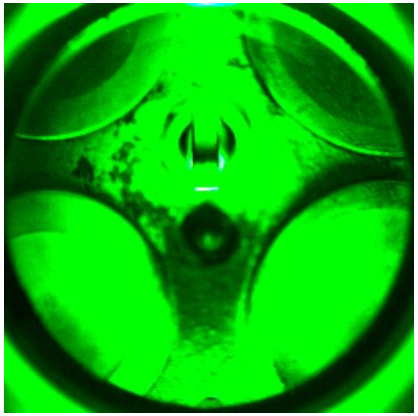
- ϕ_m = 0.33, SOI_{a1} = -40°CA, SOI_{a2} = -25°CA, Tail Ignition.
- E30 has highest smoke.
- Hypotheses: **A.** Wall-affected soot formation (*aka* pool fires) is an important pathway for exhaust smoke. It is promoted by the stronger vaporization cooling associated with ethanol.
- **B.** NO_x / PM trade-off with EGR suggests that engine-out smoke is limited by soot-formation rates for E30.
- Alkylate burns very cleanly.
- Wall wetting should be sensitive to wall temperature.
- Check response for E30 – see slide 30.



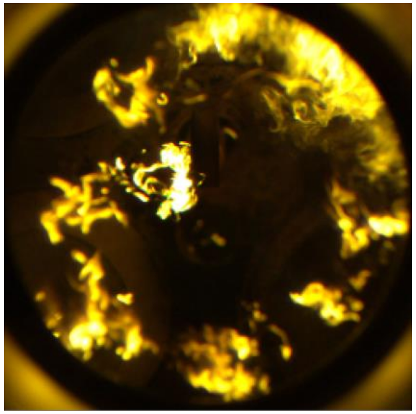
Visualization of Soot Deposits for E30

- At 1000 rpm, soot-deposit formation is impeded by reduced $[O_2]$.
- Strengthens hypothesis B.
- Boosted 2000 rpm has very little soot deposit formation.

Before



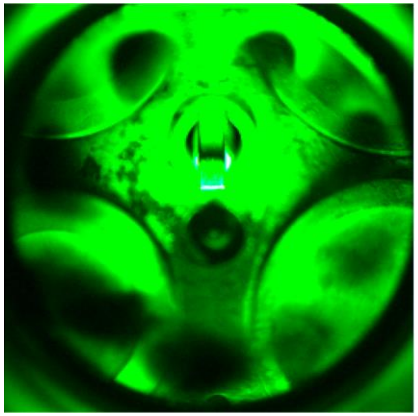
Combustion



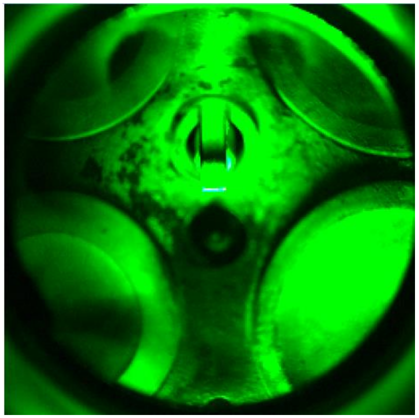
	Average image intensity (a.u.)			
	A	*B*	*C*	*D*
Before	105	81	90	87
After	79	69	83	87
Change	- 25 %	- 15 %	- 8 %	0 %

After combustion

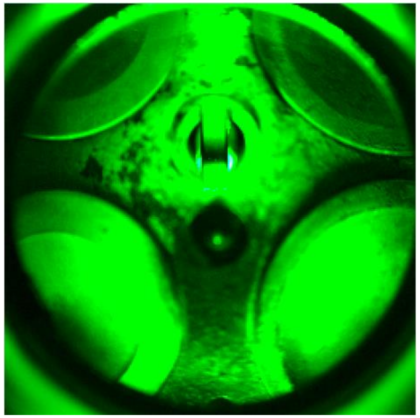
A) *1000 rpm, 100 kPa, Double Injection,* O_2 *= 18%*



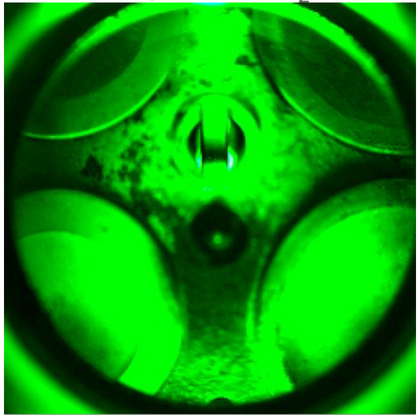
B) *1000 rpm, 100 kPa, Double Injection,* O_2 *= 16%*



C) *2000 rpm, 130 kPa, Double Injection,* O_2 *= 19 %*

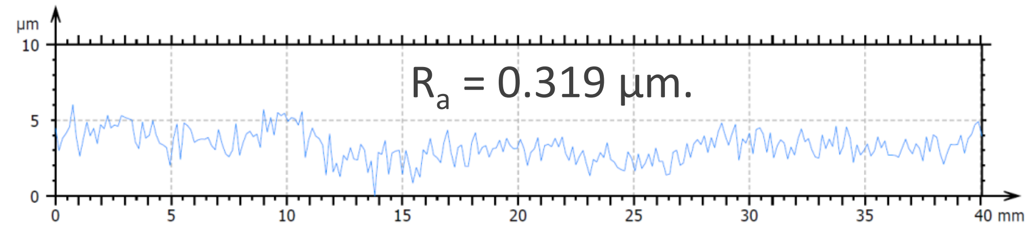


D) *2000 rpm, 130 kPa, Double Injection,* O_2 *= 17%*

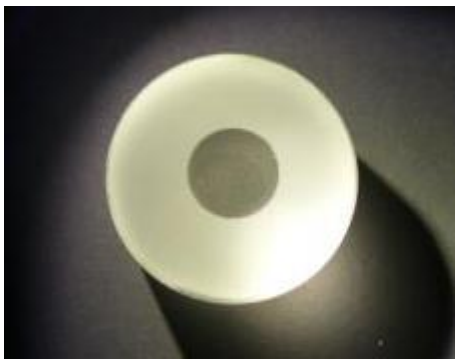


Wall-Wetting Diagnostics

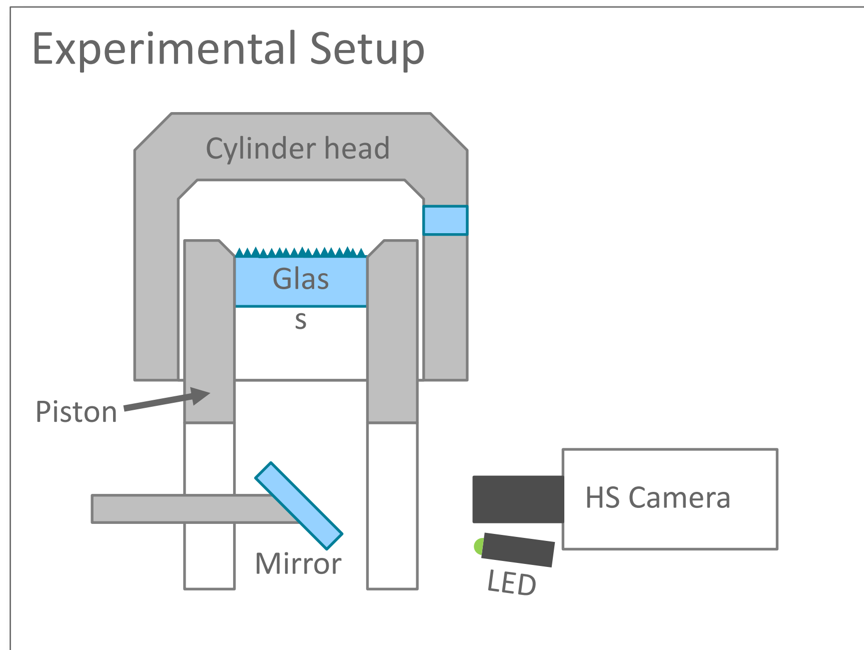
- Use Refractive Index Matching (RIM) to detect fuel films, following Fansler, Drake *et al.* (e.g. SAE Paper 2003-01-0547.)
- Use piston window with unpolished "milky" surface.



Illumination with flash lamp from the side

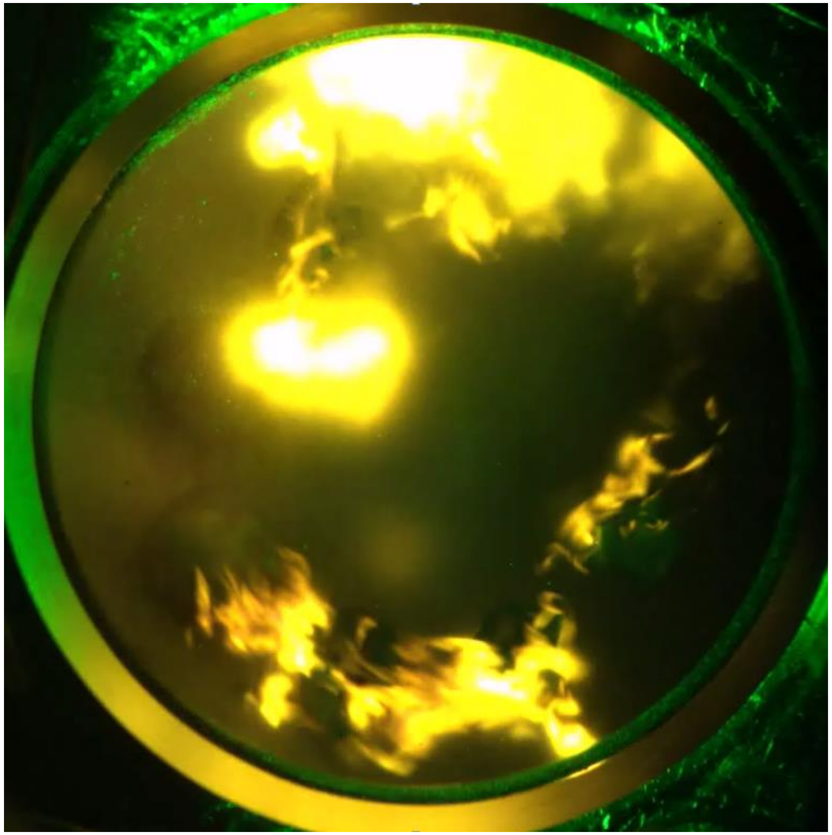


7 mm lifted on one side – sharp image close to surface

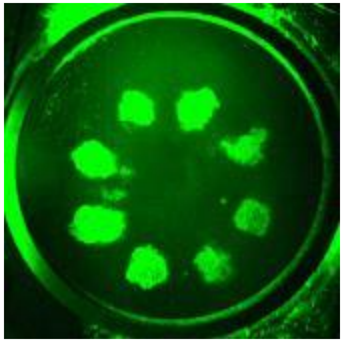


Flame Imaging with Milky Window

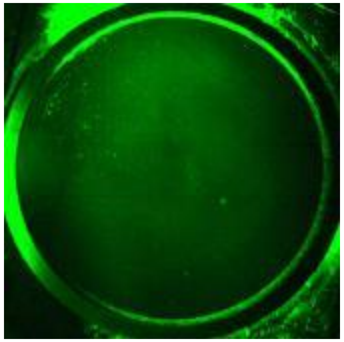
1000 rpm, 100 kPa, single injection, E30 fuel



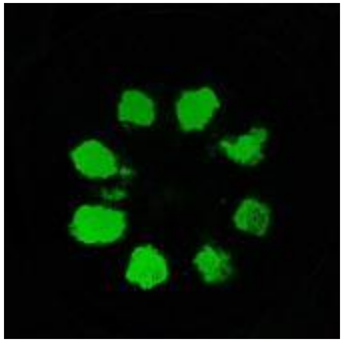
Wall-Wetting Diagnostics



liquid film image

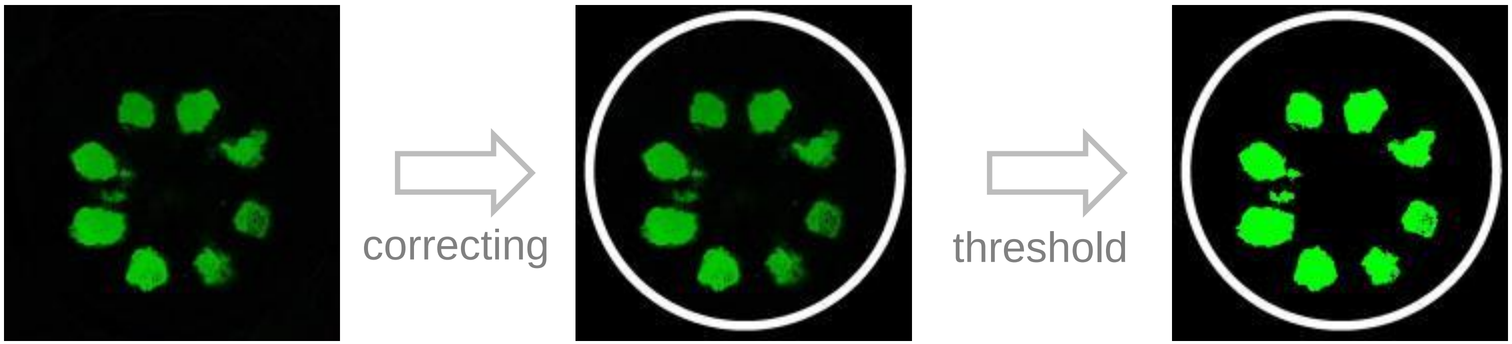


reference image



subtracted image

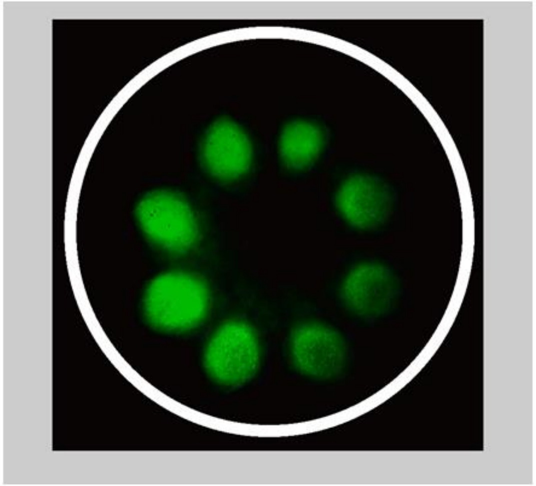
Wall-Wetting Diagnostics



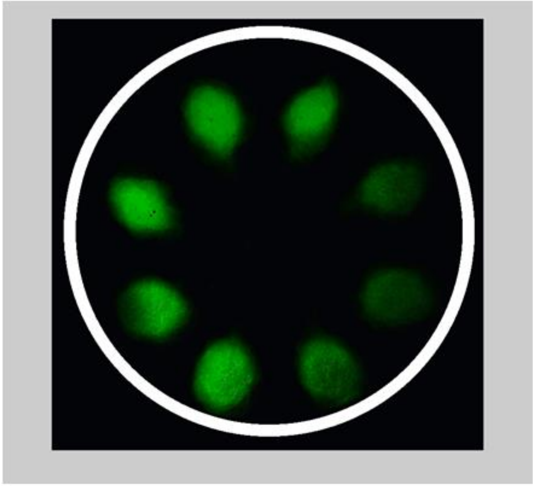
subtracted image | add mask | liquid film area

Wall-Wetting Diagnostics

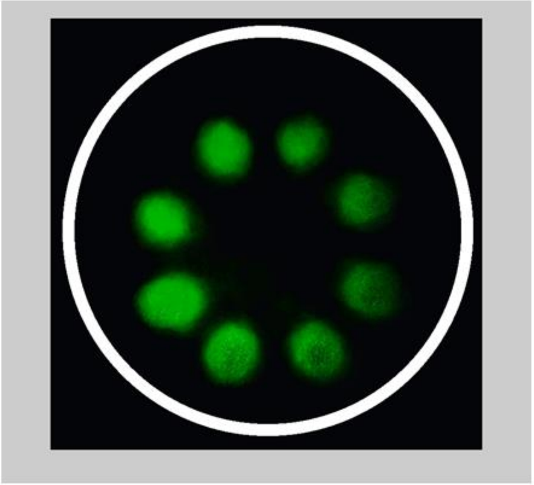
E30 Single Injection



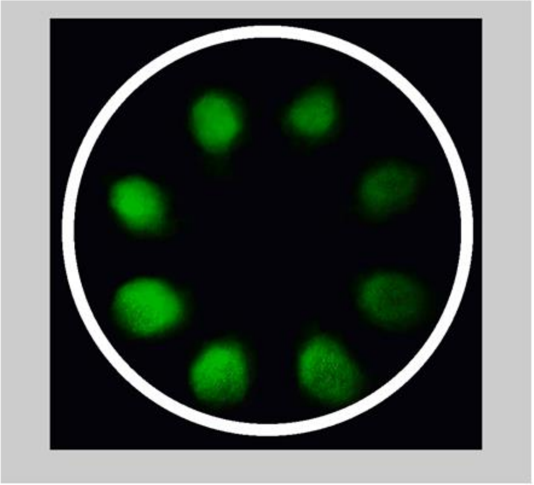
E30 Double Injection



HA Single Injection

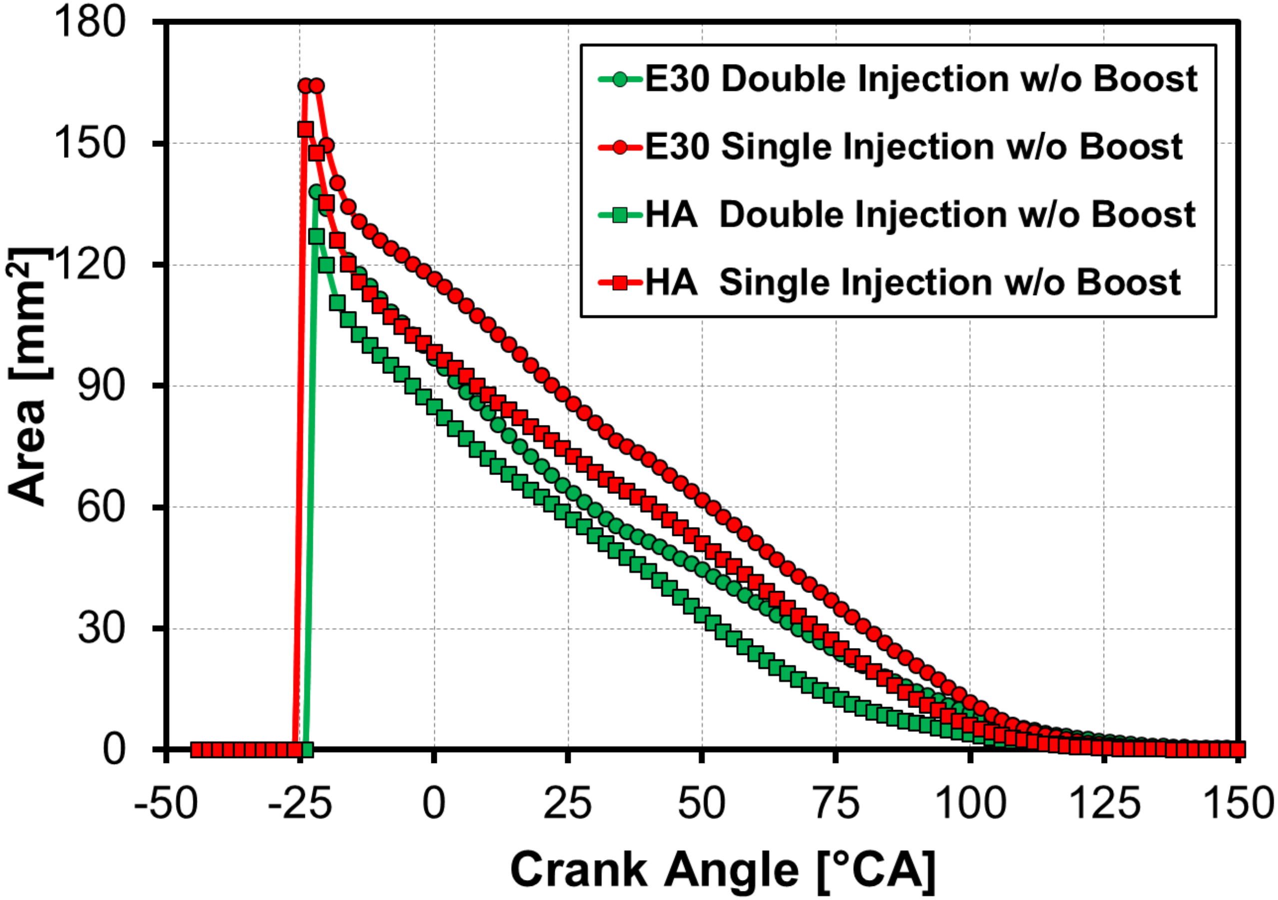


HA Double Injection



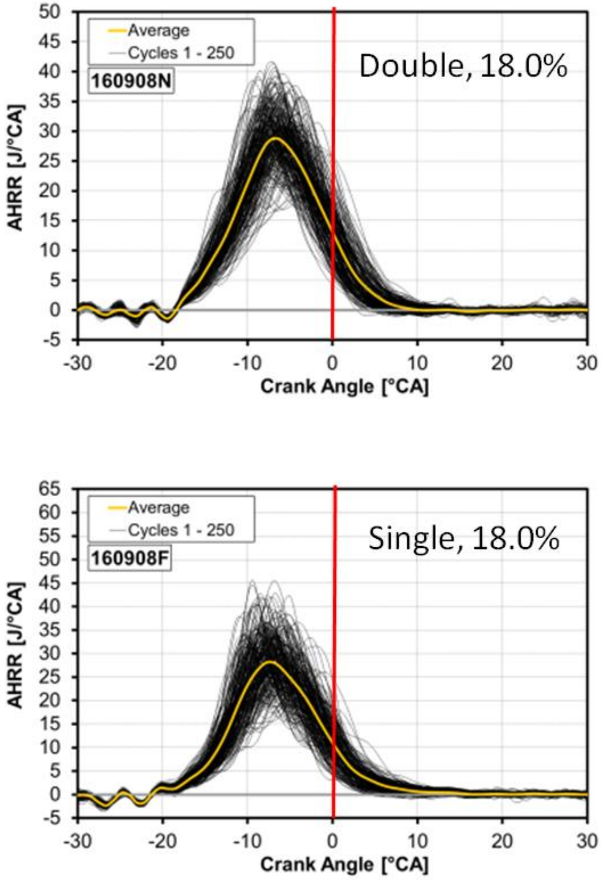
Single vs Double Injection w/o Boost

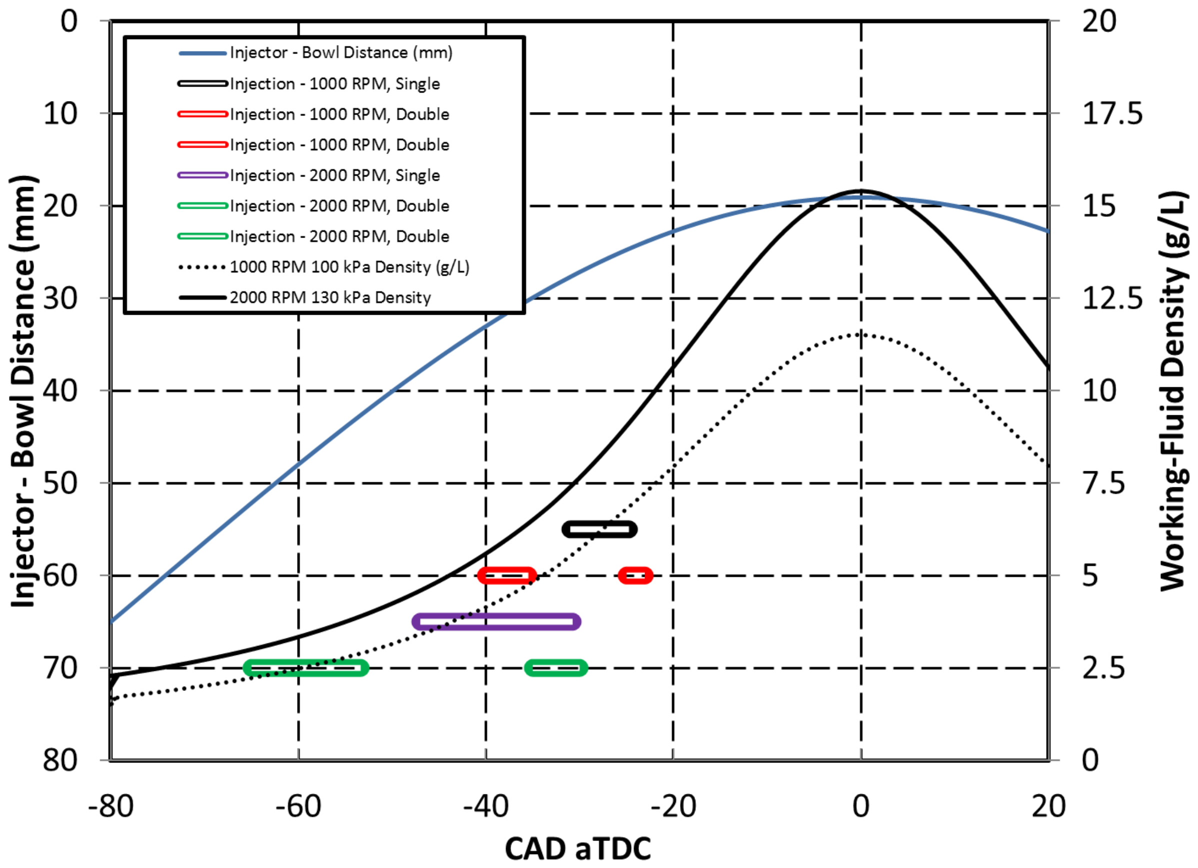
- E30 creates slightly larger wetted area, which vaporizes slightly slower.
- Working on enhanced RIM for film thickness and fuel mass.
- Double injections do not avoid wall wetting for non-boosted operation.



Basic Considerations for Double Injections

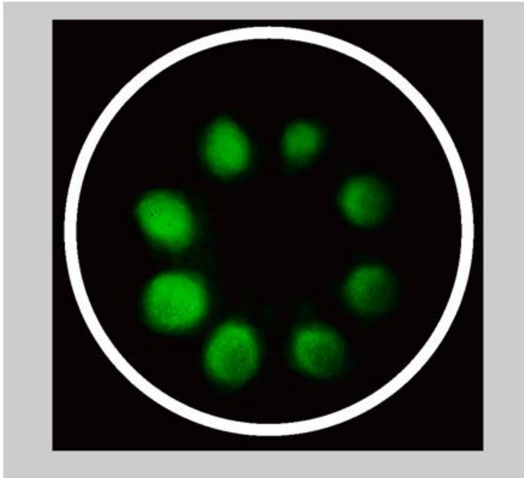
- To maintain CA50, first injection has to be conducted 9°CA earlier.
- Distance to piston bowl is greater, but density and temperature are lower.



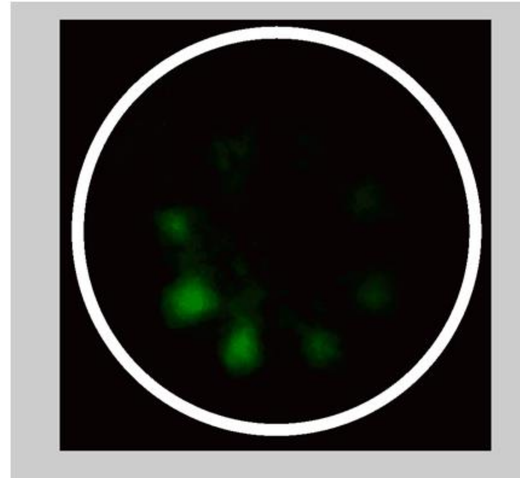


Effect of Boost on Wall Wetting

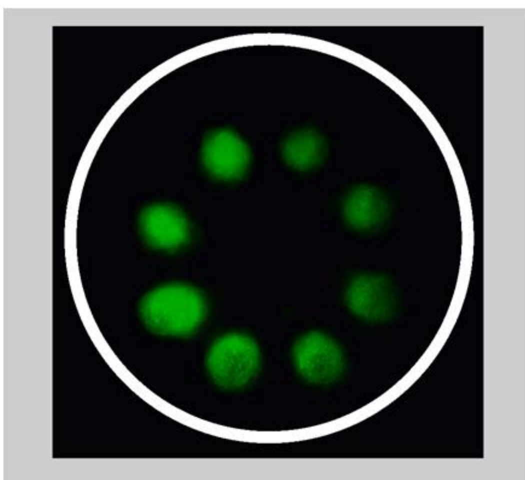
E30 w/o Boost



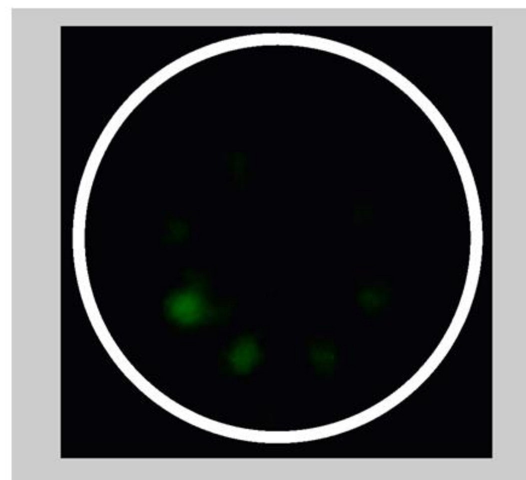
E30 w/ Boost



HA w/o Boost

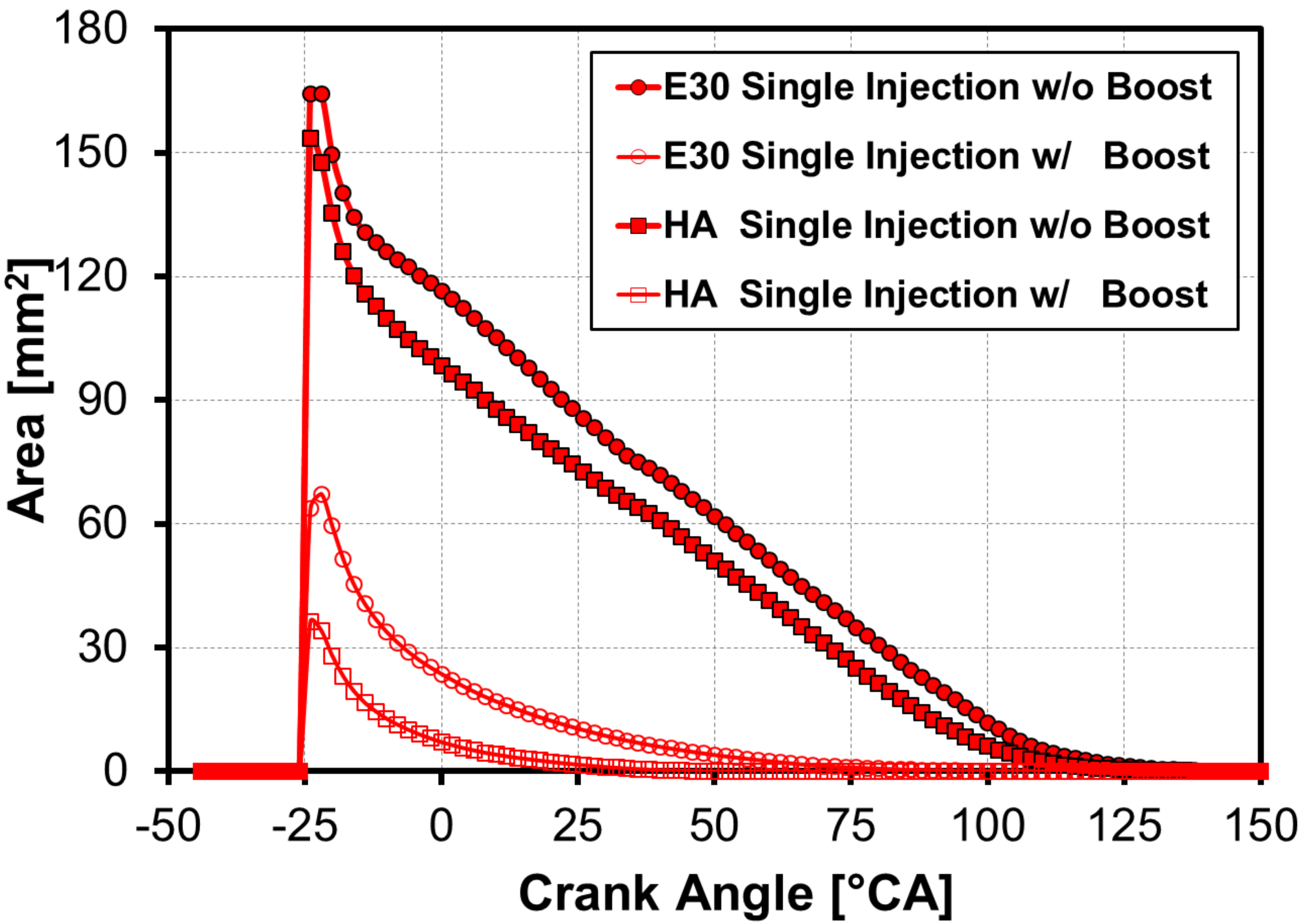


HA w/ Boost



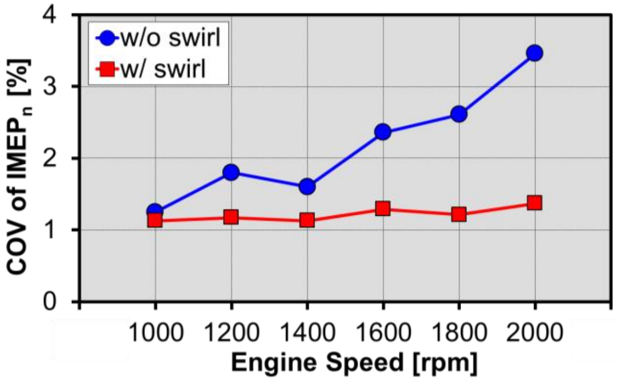
Boost vs no boost @single injection

- Moderate boost reduces wall wetting strongly.

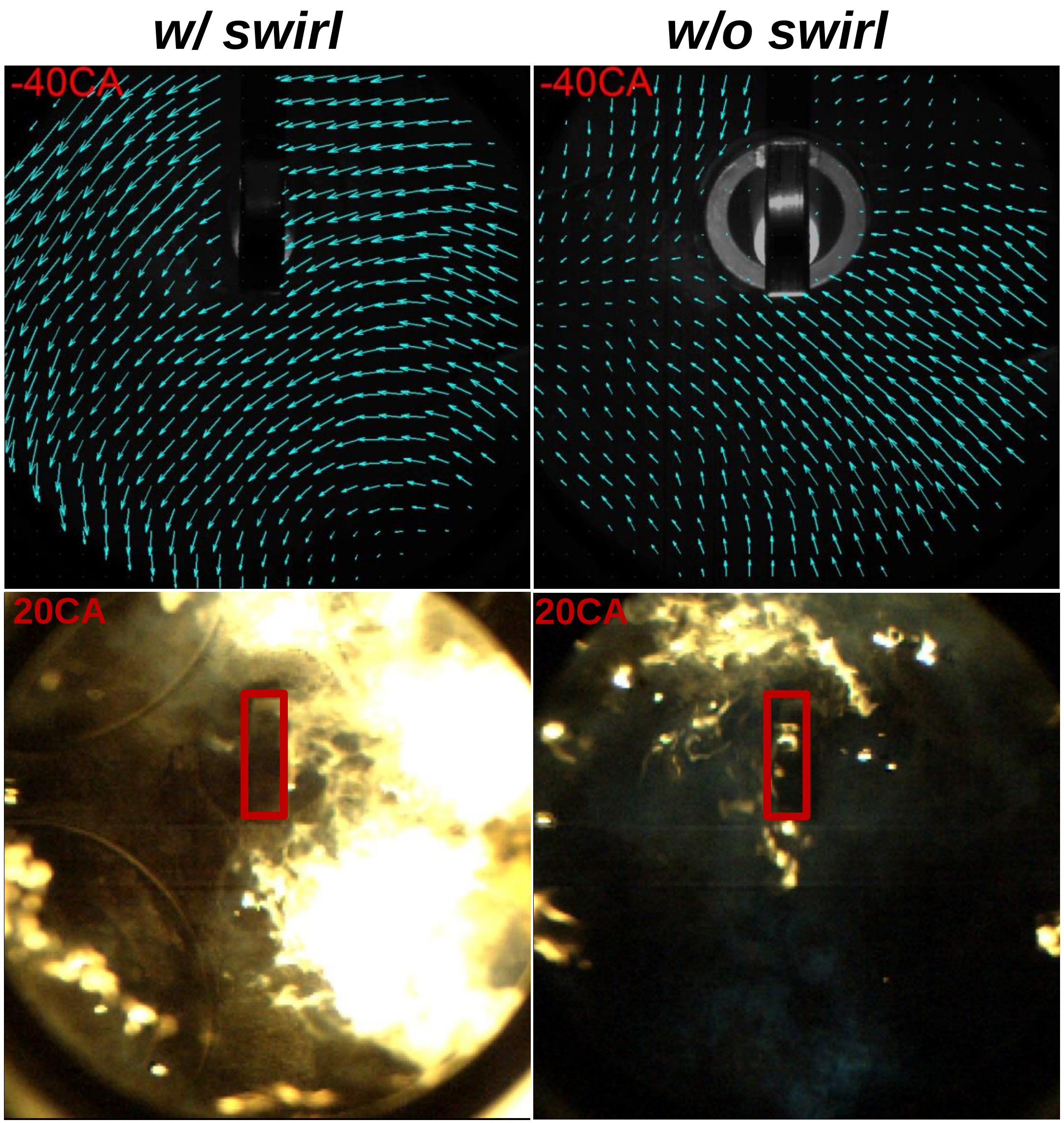


Swirl Flow Stabilizes Combustion

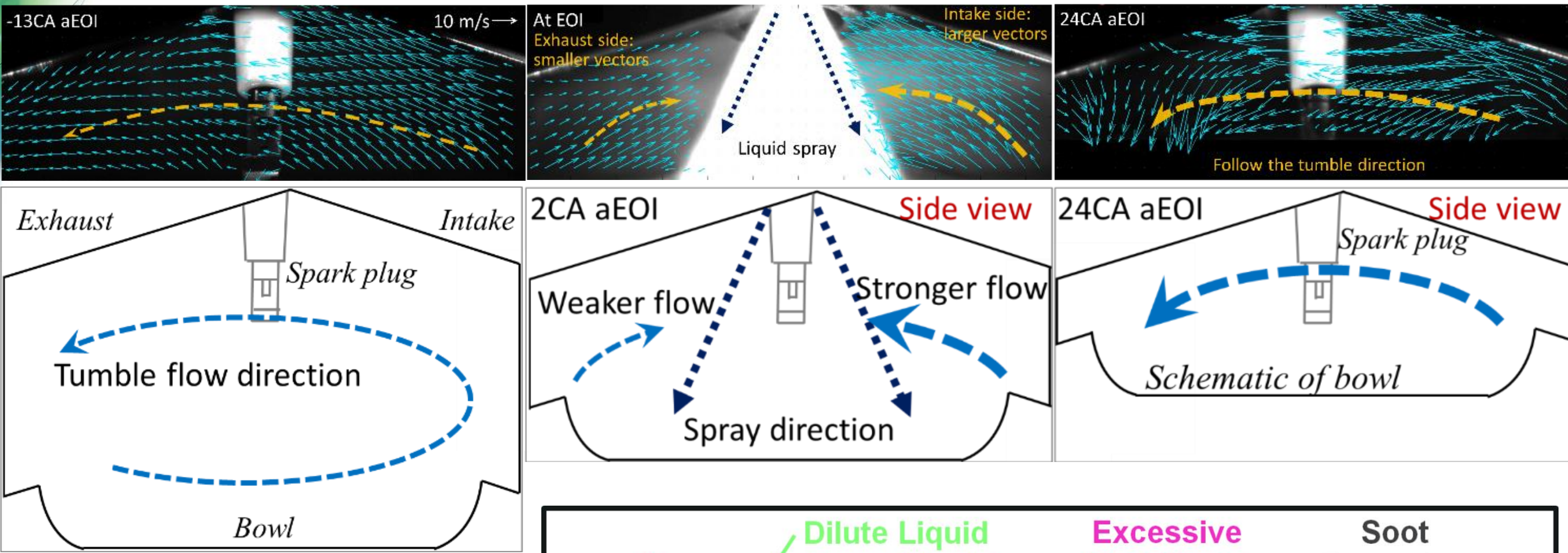
- Intake-generated swirl is required to stabilize stratified combustion at higher speeds.
  - Spray-swirl interaction creates a repeatable vortex.
  - Effective flame propagation.

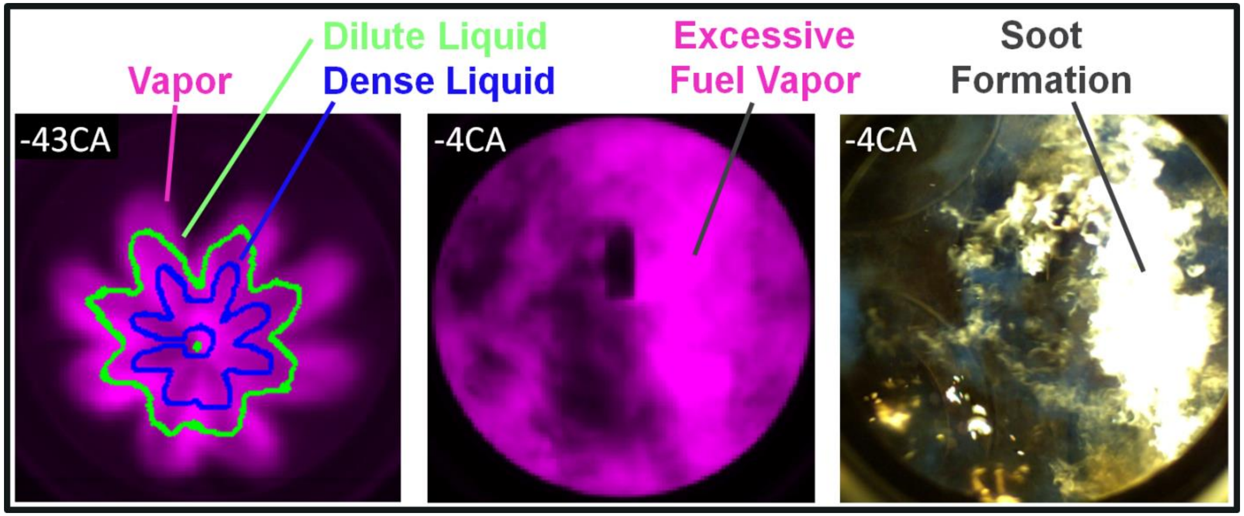


- Swirl generated by inactivating one intake valve.
  - Increases tumble as well, which can induce fuel asymmetry and elevated soot emissions.



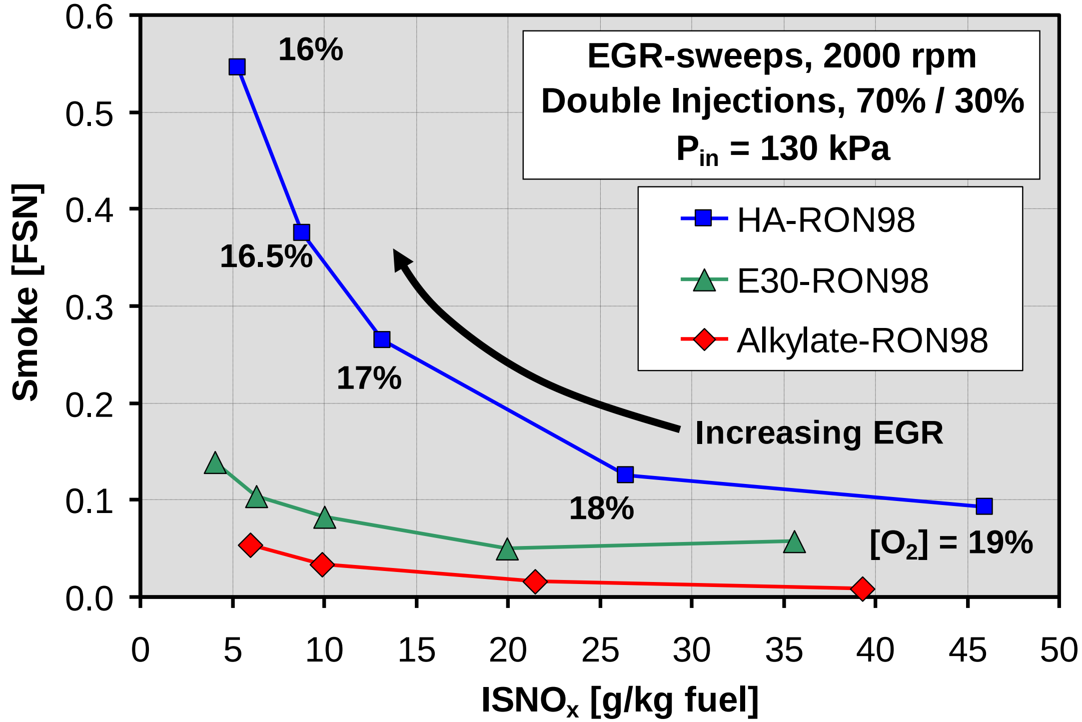
Tumble Effect on Vapor Spread





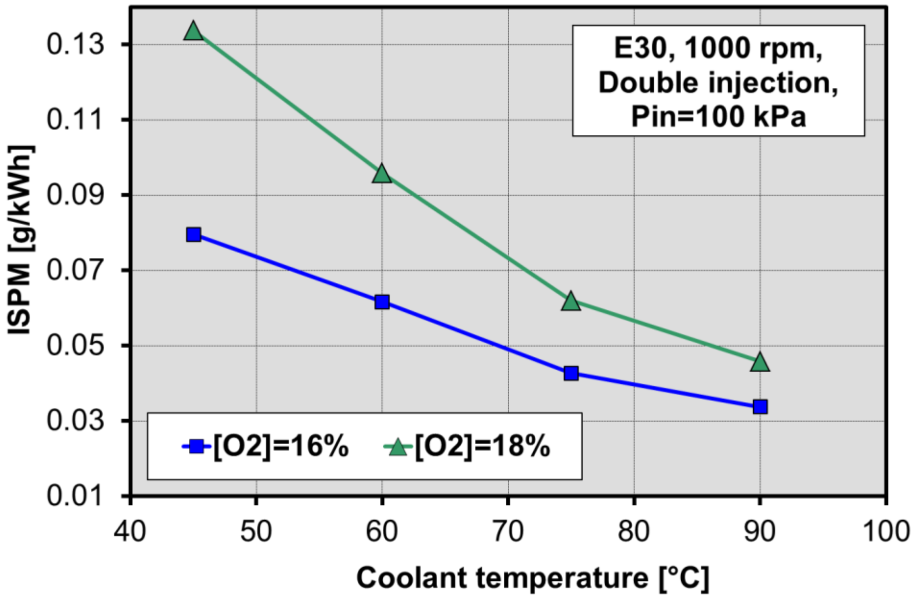
Boosted Higher-Speed Operation

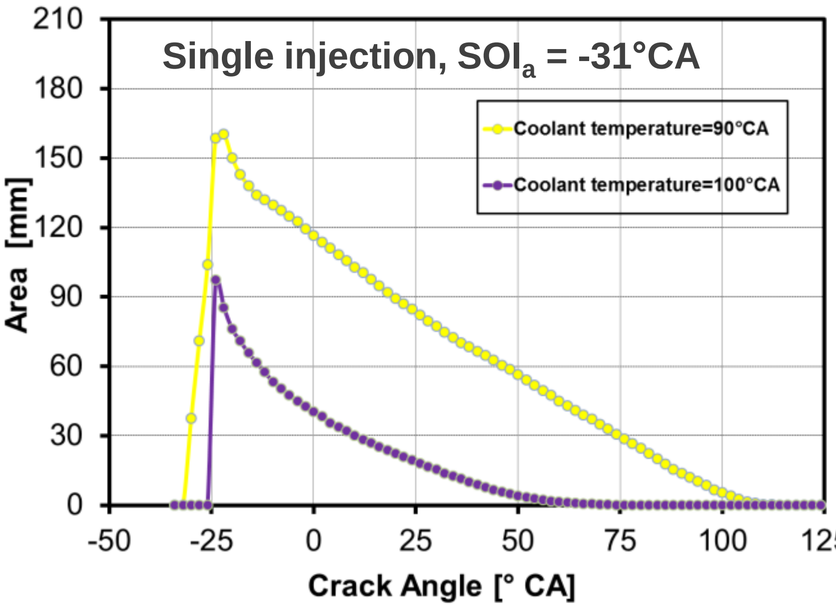
- ϕ_m = 0.33, 2000 rpm, P_{in} = 130 kPa, SOI_{a1} = -65°CA, SOI_{a2} = -35°CA.
- High Aromatics gasoline has highest smoke.
- NO_x / PM trade-off with EGR suggests that engine-out soot is controlled by oxidation rates, similarly to that observed for diesel engines.
- Hypotheses: **C.** Bulk-gas soot formation is the dominating pathway for exhaust smoke.
- **D.** For soot formation, fuel chemistry dominates over physical properties like vaporization cooling.
- This is work in progress.



Coolant Temperature Effect for E30

- 1000 rpm, P_{in} = 100 kPa.
- A reduction of coolant temperature strongly increases the soot emission for non-boosted operation.
- Available RIM data for similar conditions suggest that increased wall wetting is responsible.





Summary and Conclusions

- Fuel effects are very strong for stratified-charge SI operation.
- This needs to be carefully addressed when a new fuel is developed for market introduction, especially with new bio-based molecules.
- Propensity to smoke is addressed by identifying soot-formation pathways. Current hypotheses address two:
- 1. Wall-affected soot formation (*aka* pool-fires.)
  - Promoted by low P_{in}, high $[O_2]$ and low coolant temperature.
- 2. Bulk-gas soot formation.
  - Dominating pathway for boosted operation at 2000 rpm.
  - Oxidation is promoted by high $[O_2]$.
- Alkylate fuel shows superiorly low smoke.
  - No aromatics and low end-boiling point.
- High-aromatics fuel have worst smoke emission for bulk-gas soot conditions. Fuel chemistry dominates.
- E30 fuel have worst smoke emissions for wall-affected soot formation. Vaporization properties have increased importance.

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Extra Material

- Review of existing Gasoline-Ethanol results
- 1000 rpm, Pin = 95 kPa, $IMEP_n$ of 260 kPa.
- RD3-87 gasoline mixed with ethanol.
  - RD3-87 has 24.5% Aromatic content by volume.
- Smoke varies non-monotonically with ethanol content.
- Mid-level blends could pose a PM problem for stratified-charge SI operation.