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Dilution and Injection Pressure Effects on Ignition and Onset of Soot at Threshold-Sooting Conditions by Simultaneous PAH-PLIF and Soot-PLII Imaging in a Heavy Duty Optical Diesel Engine

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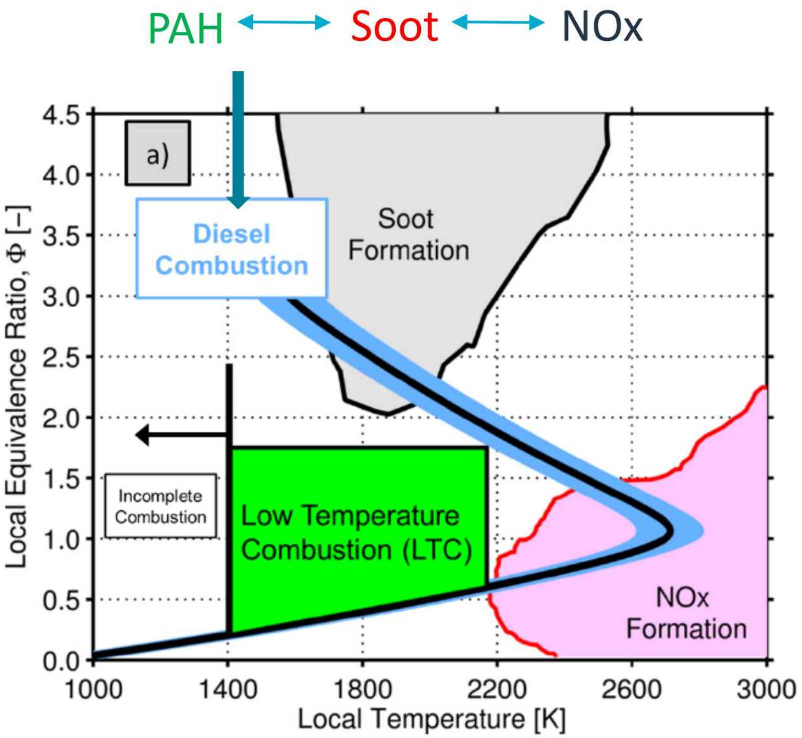
Objectives: why study soot formation?

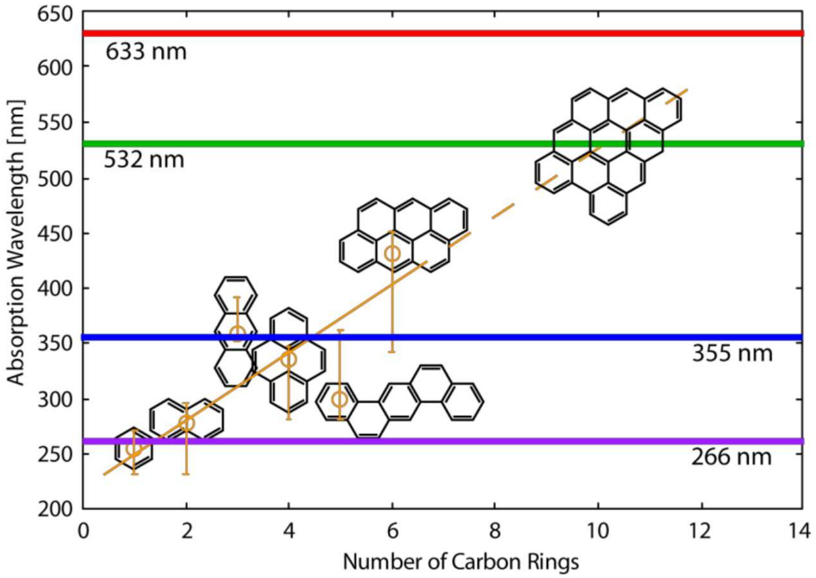
- Soot and NOx trade-off challenge.
- Engine-out soot is the net difference between soot formation and soot oxidation.
- There are many optical diagnostics for in-cylinder soot, including instantaneous quantitative measurements.
- While net soot can be measured, separating soot formation from soot oxidation with optical diagnostics is much more difficult.
- Evidence of multiple-injection effects on soot formation (our ultimate goal) is less plentiful than on oxidation.
- Poly-Aromatic Hydrocarbons (PAH) are key soot precursors, so they can provide additional insight about formation.

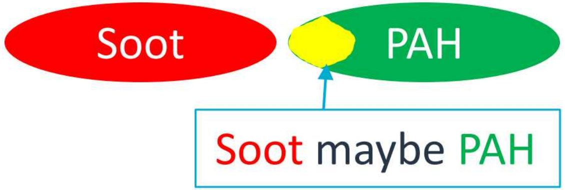


Dempsey A, Curran S, Wanger R, *Int. J. Engine. Res.* 17(8):897-917,2016

Multi-wavelength PLIF and PLII: PAH growth and soot formation

- PAH is not a single component, but rather a range of molecular sizes with different numbers of connected aromatic rings that are synthesized during rich combustion.
- As PAHs grow and accumulate more carbon/aromatic rings, their absorption spectra shift to longer wavelengths.
- Planar laser-induced fluorescence (PLIF) using different excitation (laser) wavelengths (355, 532, 633 nm) can probe growth of PAHs.
  - Problem: any of these excitation wavelengths can also induce soot incandescence interference.
- Combined with simultaneous planar laser-induced incandescence (PLII) using an IR laser (1064 nm) where PAHs are not expected to be excited, can also probe soot without PAHs.



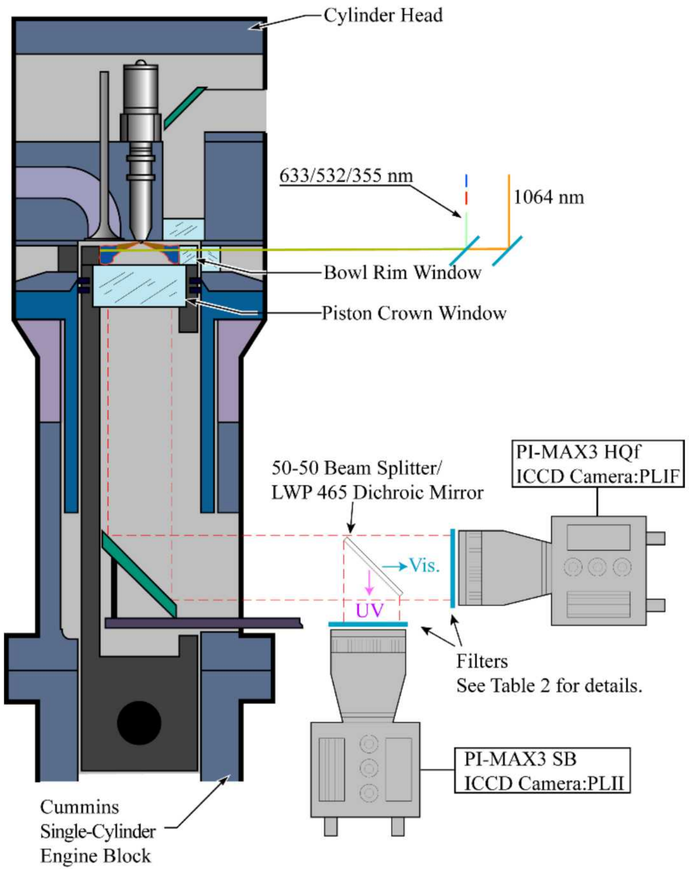


Planar PAH-PLIF using one of three laser excitation wavelengths and simultaneous soot-PLII

- All PAH-PLIF are collected using the same camera and objective.
- Both cameras are using their respective minimum intensifier gate times.
- Different spectral filters are applied according to different laser excitation wavelengths.
- PLII laser pulse is 2.5 µs later than the PAH-PLIF laser pulse to avoid signal cross-talk.

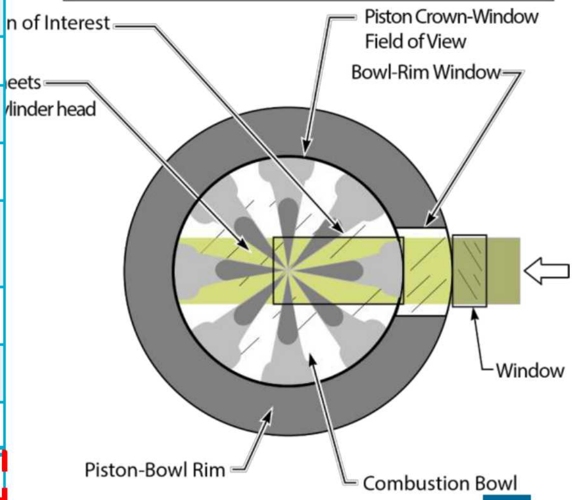
Diagnostic	PAH-PLIF	PAH-PLIF	PAH-PLIF	soot-PLII
Laser [nm]	355	532	633	1064
PAH rings	2-4 (small)	4-8 (medium)	10+ (large)	Soot
Camera	PI-MAX3 HQf			PI-MAX3 SB
Camera lens	Nikkor 105 mm, f/2.5			
Intensifier gate [ns]	2.54			275
Spectral Filters	GG-395 SWP-850	XNF-532.0 SWP-850	XNF-632.8S WP-850	SWP-450 GG-385
Detection Range [nm]	395-850	465-850 (- 532 notch)	465-850 (- 633 notch)	385-450
Beamsplitter	50-50 broadband	LWP 465 dichroic	LWP 465 dichroic	as PAH-PLIF
Laser pulse energy [mJ]	~70	~70	~70	~250

Engine and optical setup: PAH-PLIF using one of three laser excitation wavelengths and simultaneous soot-PLII



Engine base type	Cummins N-14, DI diesel
Number of cylinders	1
Number of intake valves	2
Number of exhaust valves	1*
Combustion chamber	Quiescent, direct injection
Swirl ratio	0.5
Bore × stroke, [cm]	13.97 × 15.24
Bowl width, depth, [cm]	9.78, 1.55
Displacement, [liters]	2.34
Connecting rod length, [cm]	30.48
Geometric compression ratio	11.2:1
Fuel injector type	Common-rail, solenoid actuated Delphi DFI-1.5
Number of holes & arrangement	8, equally-spaced
Nominal orifice diameter, [mm]	0.131
Included spray angle	156˚
Fuel type	n-Heptane

Top view of Current Work:
Piston-bowl window, horizontal sheets



Engine operating conditions: CR fuel-pressure sweep and intake O_2 sweep

	P_{rail} [bar]	533	800	1200
7.5% O_2	PAH-PLIF [nm]		633	
	IMEP [kPa]		396	
9.0% O_2	PAH-PLIF [nm]	633	355, 532, 633	633
	IMEP [kPa]	449	582	690
10.0% O_2	PAH-PLIF [nm]		355, 532, 633	
	IMEP [kPa]		666	
12.5% O_2	PAH-PLIF [nm]		355, 532, 633	
	IMEP [kPa]		778	
15.0% O_2	PAH-PLIF [nm]		633	
	IMEP [kPa]		817	
CR SSE, [CAD]			347	
CR DSE, [ms]			4	
Engine Speed, [RPM]			1200	
IMEPg [kPa]			396-817 (see rows above)	
Skip fire ratio			1:9 (1 fired followed by 9 motored cycles)	
Intake temperature, [°C]			110	
Intake pressure, [kPa]			220	
Estimated TDC temperature, [K]			900	
Estimated TDC density, [kg/m³]			22.8	

CR fuel-pressure and O_2 dilution sweep →

Injection same →

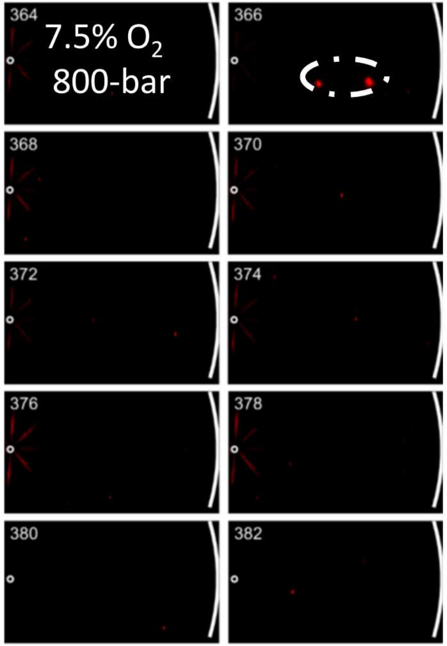
Load varies →

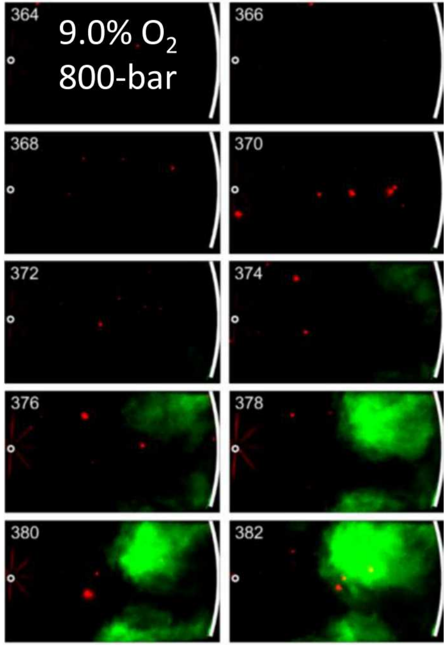
Intake aiming at ECN conditions →

Intake-O_2 sweep results: 7.5% O_2 shows neither PAH nor soot, at 9.0% O_2 PAH appears late in the cycle

- 633-nm PAH-PLIF shows "final" PAH, we focus mostly on the 633-nm results. The images shown are ensemble-averaged.
- At 7.5% intake-O_2 800-bar injection pressure,

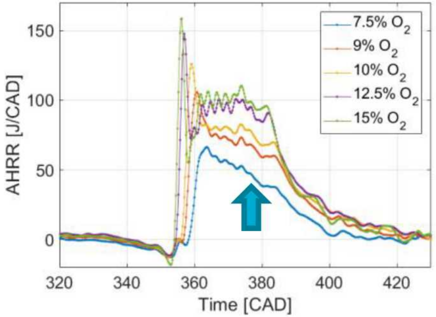
- At 9.0% intake-O_2 800-bar injection pressure, large PAH (633-nm excitation) appears at 374 CAD





633-nm PAH-PLIF

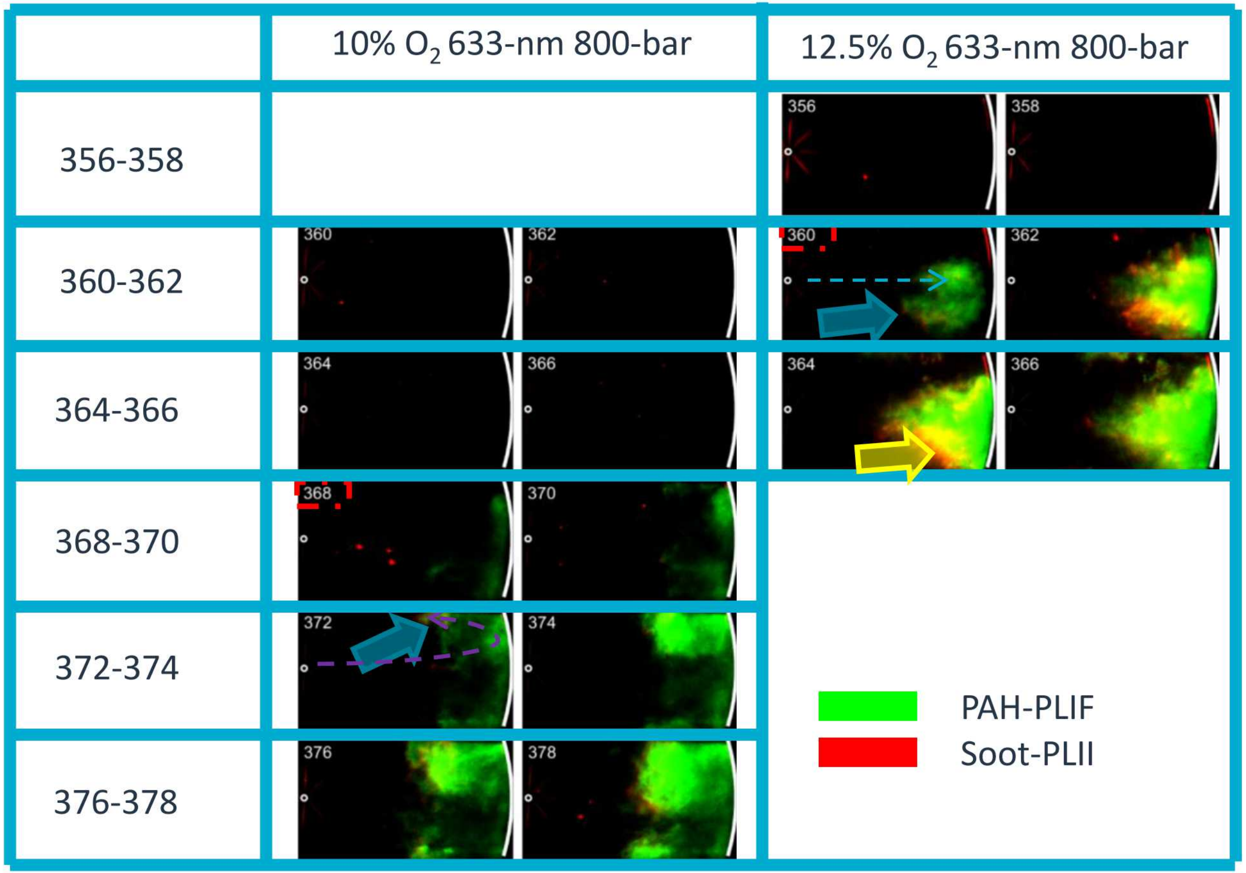
Soot-PLII



CR fuel-pressure kept constant at 800 bar

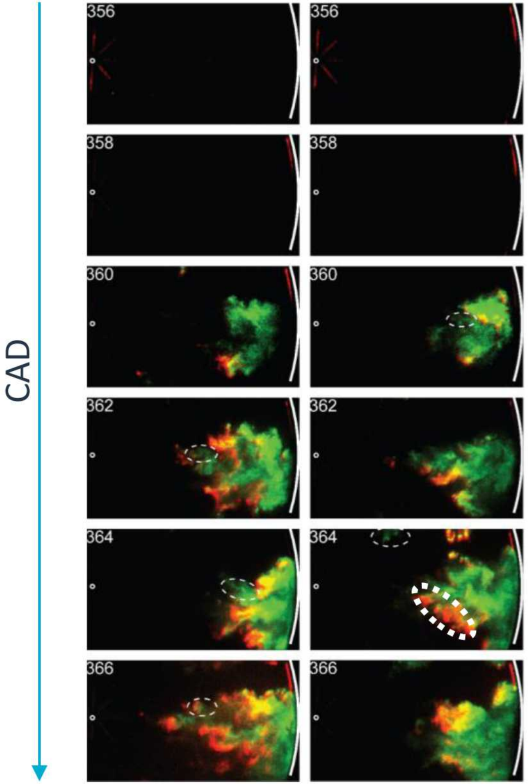
Intake O_2 sweep results: soot appears at 10%, at 12.5% initial PAH appears 8˚CA earlier than 10%

- With intake-O_2 increased to 10%,
- PAH first appears at 360 CAD for 12.5%, 8˚CA earlier than for 10%
- Soot also forms earlier at 360 CAD for 12.5% than for 10% and the initial soot apparent location is different
- Soot-PAH overlap is apparent for 12.5%
- Ensemble-averaging effect or real soot and PAH overlap?



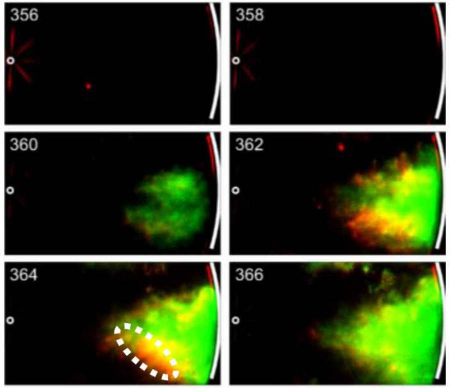
Intake O_2 sweep: instantaneous images

12.5% O_2 633-nm 800-bar
INSTANTANEOUS images

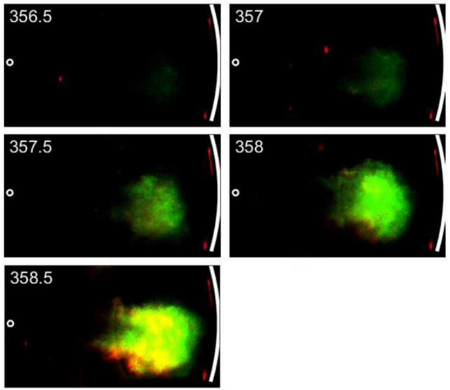


- Each composite instantaneous image is from a different engine cycle.
- Compared to ensemble-average images, the instantaneous images show evidence of less overlap between soot and PAH (the yellow region), and soot is on jet periphery, upstream of PAH.
- PAH sometimes appears 'down-beam' of soot, so minimal PAH/soot overlap is not likely an artifact of attenuation of the PLIF laser sheet.
- PAH is consumed and/or absorbed by soot.

12.5% O_2 633-nm 800-bar
ENSEMBLE-AVERAGE images



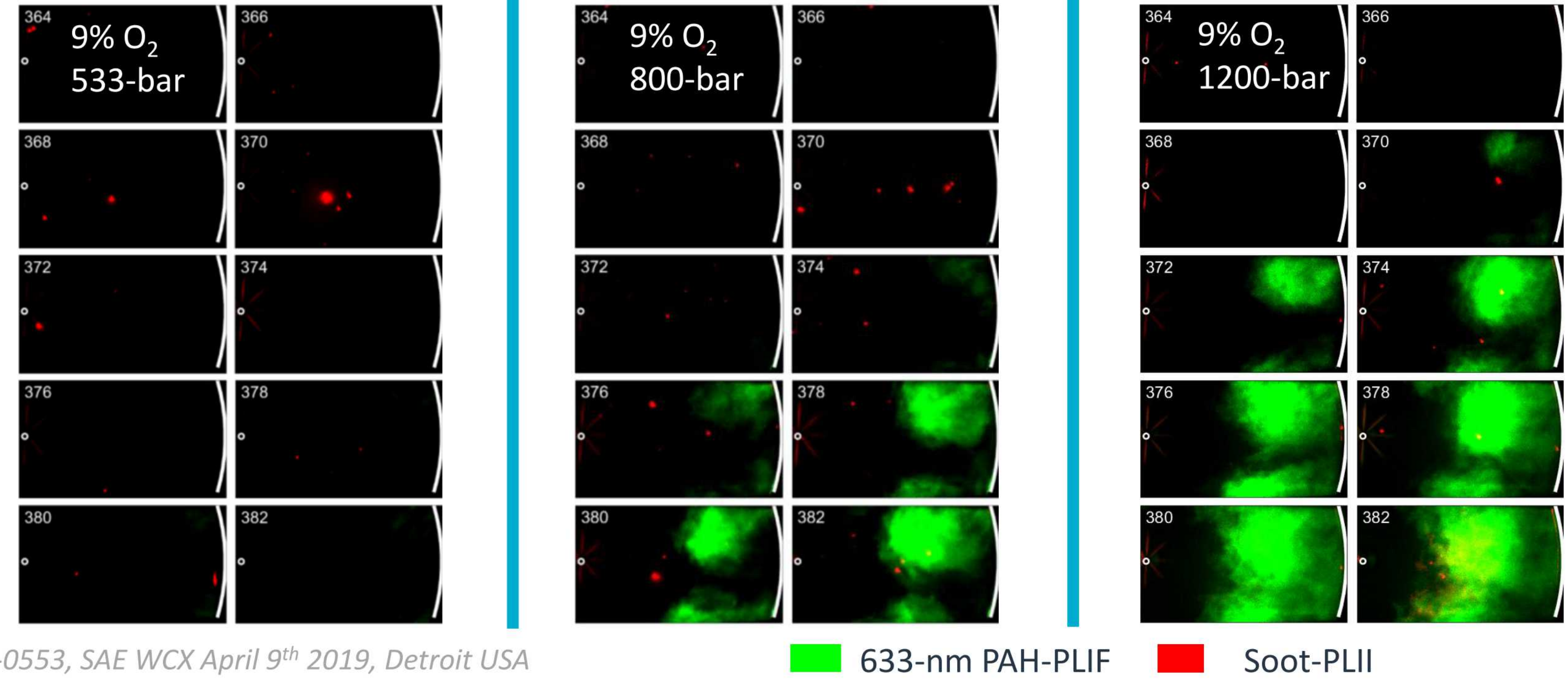
15.0% O_2 633-nm 800-bar



PAH-PLIF Soot-PLII

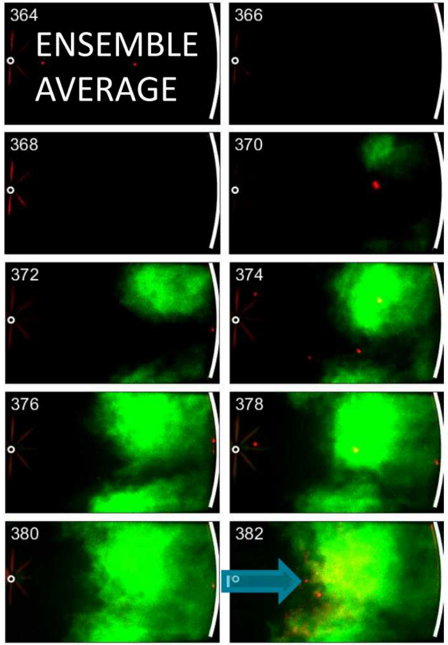
CR fuel-pressure sweep results: more PAH forms with increasing pressure, soot appears at 1200-bar only

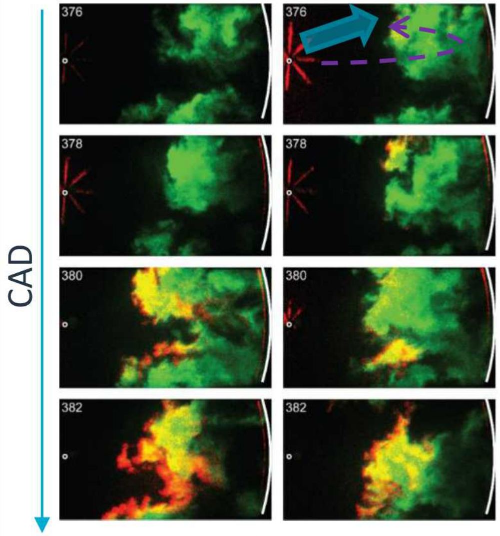
- The intake O_2 mole-fraction is kept as constant at 9%, but CR pressure is increased.
- SSE and DSE are also held constant for all three cases, so engine load increases with CR pressure.
- PAH increases with increasing CR pressure.
- Soot appears at 382 CAD for 1200-bar only.



CR fuel-pressure sweep results: more PAH forms with increasing pressure, soot appears at 1200-bar only

- Soot is first apparent in the ensemble-averaged images at 382 CAD,
- Soot does not always appear among all 12 replicates at 376 and 378 CAD due to cycle-to-cycle variation. Of the 12 replicates at each CAD, soot appears 11 and 12 times at 380 and 382 CAD, respectively. Soot first appears consistently in nearly every cycle at 380 CAD.





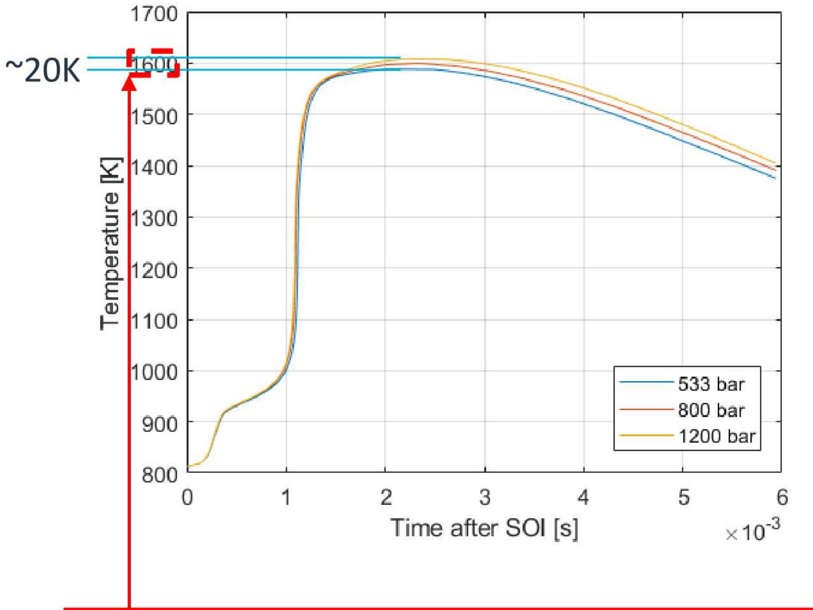
INSTANTANEOUS
Soot-PLII(red)
images re-scaled

	633 PAH-PLIF	Soot-PLII
533-bar	No	No
800-bar	374 CAD	No
1200-bar	370 CAD	380 CAD

Intake-O_2 9%, 633-nm

0-D simulation shows little temperature differential from 533 to 1200 bar CR pressure; local temperature differential could be larger

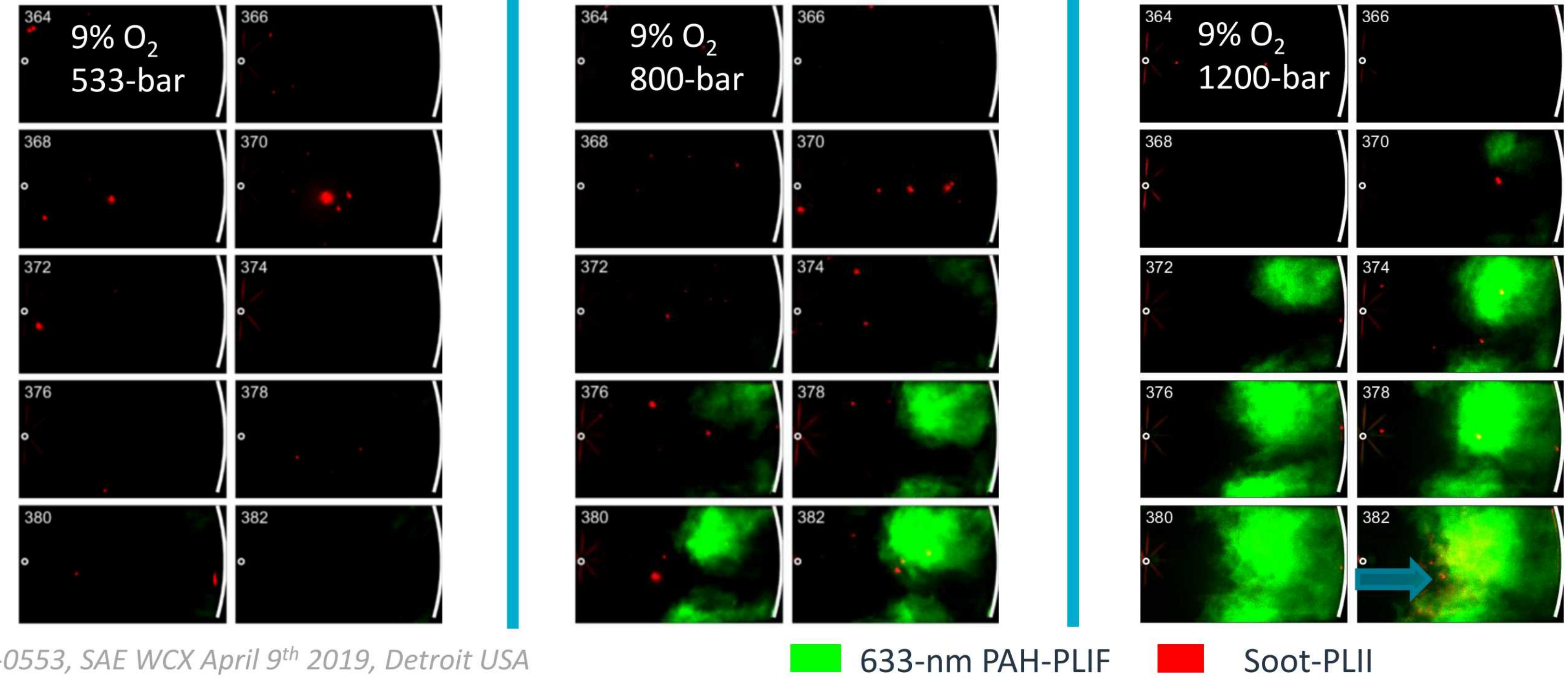
- Chemkin Pro 0-D simulation.
  - N-heptane mechanism from Wang et al. *Int. J. Engine. Res., 2013*
  - The measured cylinder-pressure constrains the adiabatic reacting compression simulation.
- The temperature differential between the highest and lowest CR fuel-pressures is only 20 K. Considering the additional thermal energy from increasing injection velocity, the estimated mixture temperature differential is at most about 27K.
- In a previous work by Pickett et. al, Two-Stage Lagrangian simulations have shown that faster mixing due to increased turbulence at higher injection pressure can increase local temperatures on the order of 100 K. *Int. J. Engine. Res., 2006*



Skeen et.al showed soot formation can vary drastically near a threshold temperature near 1600K within 50 K, which is coincidentally similar to the simulation peak compressed-gas temperature.
Combust. Flame. 188: 483-487, 2018

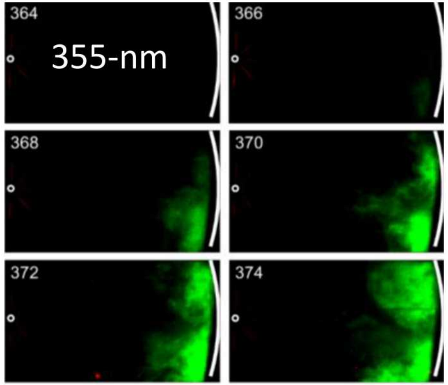
CR fuel-pressure sweep results: lift-off length explanation doesn't work for threshold-sooting condition

- Regarding the contradiction of increasing soot at higher injection pressure, the explanation of increasing entrainment upstream of the lift-off length yielding lower soot works well for quasi-steady jets at conventional diesel conditions, where both soot formation and oxidation are important.
- In this work at a threshold-sooting condition, soot formation likely dominates oxidation effects.
- Hence, PAH and soot likely form only when the local temperature threshold is crossed.

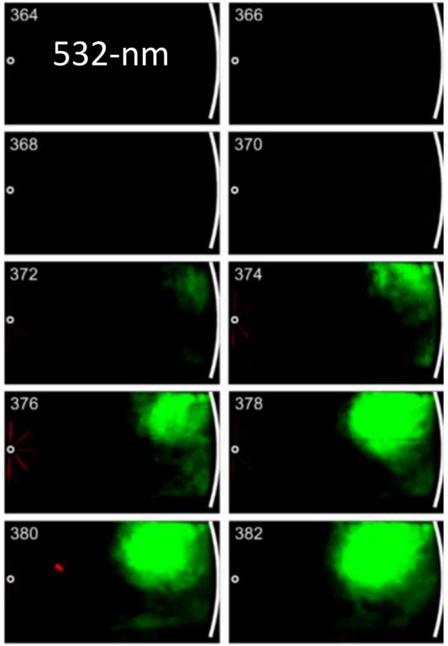


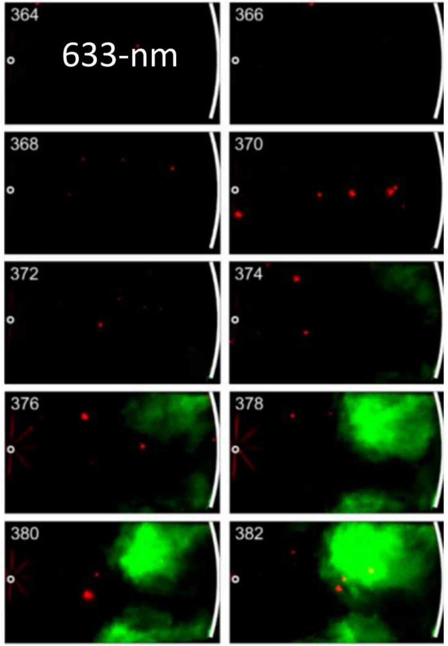
PAH-PLIF laser excitation wavelength scan: smaller PAH appears earlier and farther upstream

- Small PAH forms earliest at 366 CAD, then at 372 CAD medium PAH appears, then at 374 CAD shows large PAH at the same engine condition.
- Spatial distribution is also different. Larger PAH appears farther down stream of the jet axis than smaller PAH.



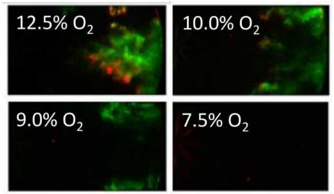
Intake-O_2 9%, 800-bar CR pressure



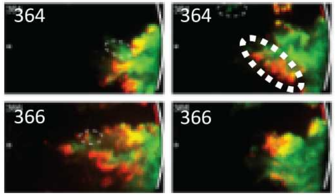


PAH-PLIF Soot-PLII

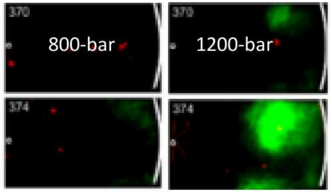
Summary



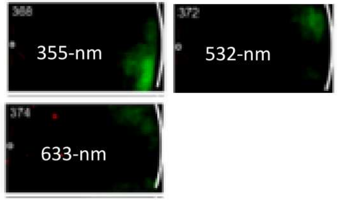
Increasing dilution delays the inception of PAH as the intake-O_2 mole-fraction decreases. Neither larger PAH nor soot are detected with 7.5% intake-O_2. Large PAH appears at 9% intake-O_2, while soot initially appears at 10% intake-O_2.



The spatial distribution of PAH and soot overlap slightly under these threshold-sooting conditions, with soot typically surrounding the PAH. The minimal overlap also suggests that PAHs are rapidly consumed and/or absorbed when soot is formed.



As the CR fuel pressure is increased from 533 to 800 to 1200 bar at 9% intake O_2, large PAH first forms at 800 bar, while soot first appears at 1200 bar. This may be explained by increased local temperatures at the higher mixing rates for the higher velocity injection.



Initial formation of larger PAH occurs later and farther downstream than smaller PAH, shifting more into the jet-jet interaction regions rather than near the nominal jet axis.

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Thank you for your attention!