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Interaction and Ignition Process of Multiple Injections of Conventional and Oxygenated Fuels in an Optical, Heavy-Duty Diesel Engine

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Abstract

Oxygenated fuels such as poly-oxymethylene ethers (POME) have demonstrated significant potential for zero-soot operation even at high exhaust gas recirculation (EGR) rates in diesel engines. When such oxygenated fuels are suitably combined with established in-cylinder strategies such as multiple injection, there may indeed be a great potential for achieving simultaneous zero-soot and near-zero nitrogen oxides (NO_X) emissions with minimal penalty on engine efficiency with the added advantage that POME fuels can be produced renewably. The ignition and combustion characteristics of POMEs have not been investigated extensively thus far, which is further complicated by the intricate dynamics of multiple injection strategies commonly employed in modern diesel engines. Furthermore, the mixing field and equivalence ratio distribution will change drastically when switching from conventional fuels to highly-oxygenated POME due to the low stoichiometric air-to-fuel ratio (AFR_{st}) associated with such fuels. Therefore, an extensive engine re-map might be crucial to fully utilize the potential of oxygenated fuels such as POME while maintaining high engine efficiencies, limiting the NO_X production and combustion noise through multiple injection. This effort can be considerably reduced through a systematic study focused on improving the understanding of the fluid-mechanical and chemical coupling between the mixing, ignition and combustion processes of the two injections, which dictates the effectiveness of multiple injection strategy. Specifically, the present study focuses on the changes in ignition and combustion characteristics of multiple injections due to differences in AFR_{st} between conventional and highly-oxygenated POME fuels.

To this end, experiments were performed in a heavy-duty, optical, single-cylinder engine to study the ignition and combustion behavior of POME under various multiple injection schedules. Identical experimental investigations utilizing n-dodecane as conventional hydrocarbon fuel due to its similar ignition delay characteristics as POMEs served as baseline data for comparison. Optical diagnostics involving simultaneous, planar laser-induced fluorescence (PLIF) imaging of formaldehyde (HCHO) and hydroxyl (OH) radical are used as an indicator of low-temperature heat-release (LTHR) and high temperature heat-release (HTHR) respectively. To complement the PLIF imaging diagnostics with time-resolved images, high-speed OH* chemiluminescence imaging and infrared (IR) imaging are acquired simultaneously to probe the ignition and subsequent combustion behavior of the two fuels under various multiple injection schedules. Parametric sweeps include variations of the intake temperature, EGR dilution rates, and multiple injection schedules by varying the mass of pilot-fuel injected and the associated dwell time that influences the ignition and combustion characteristics. Based on the imaging results and the thermodynamic analysis, conclusions are drawn on the effectiveness and optimization of multiple injection schedules and the minimal required pilot-fuel injection quantity when using POME fuels.

Motivation: Limited understanding of multiple-injection ignition process

High complexity of multiple injection ignition processes:

- Injector and schedule, charge condition and combustion chamber geometry dependence.
- *Numerous degrees of freedom* - engine noise, efficiency and emissions coupled.
- Expensive engine calibration required.

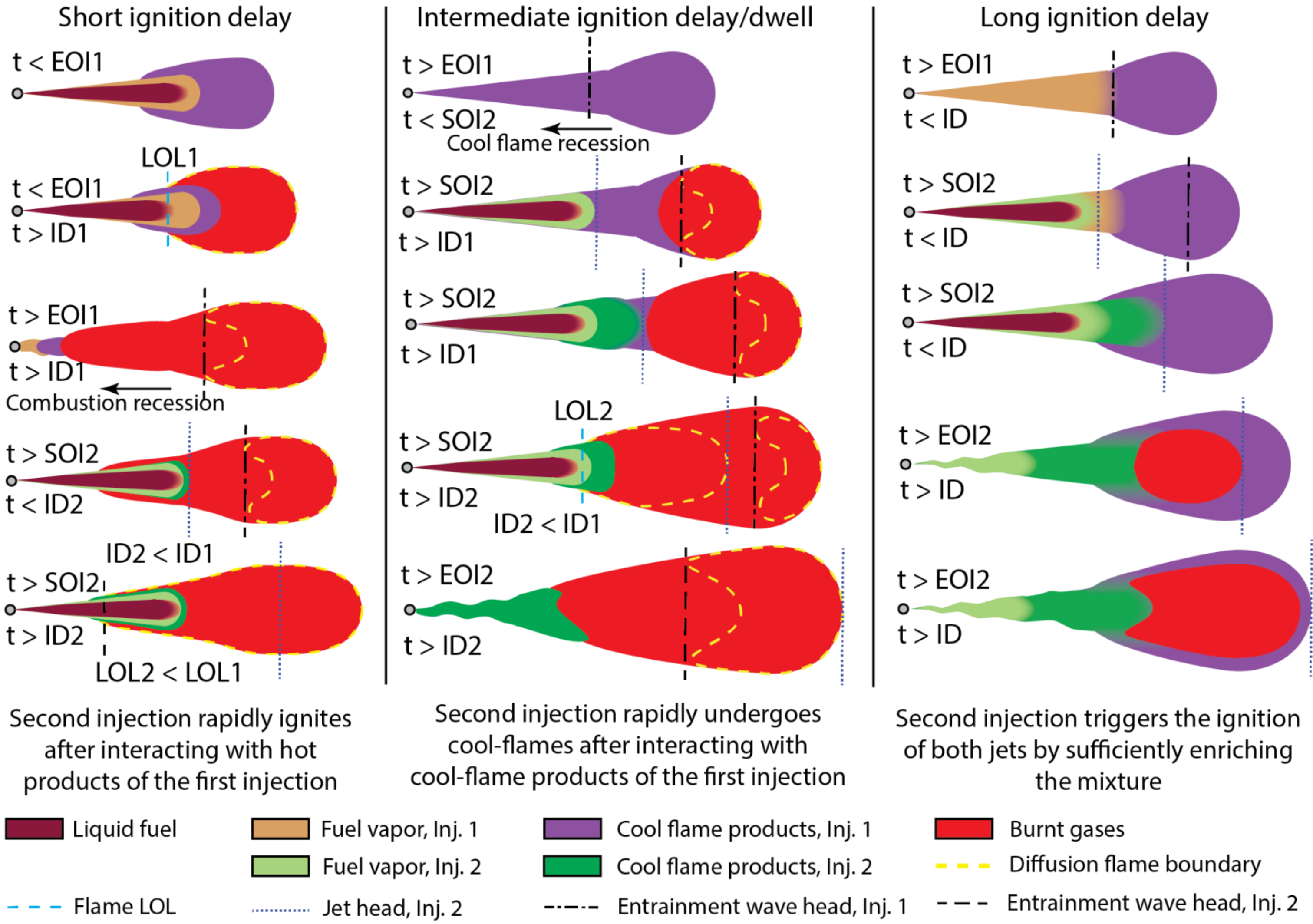
Few high-fidelity optical and CFD studies are available, plethora of metal engine studies:

- ECN split injection case is best researched (Skeen et al, SAE 2015-01-0799).
- Follow-up optical studies and high-fidelity simulations of the ECN case published.
- *No high-fidelity studies in constrained engine-relevant geometry*

Preliminary multiple-injection conceptual model composed for free-jet case:

- *Unknown* effects of jet-bowl interaction, engine swirl, pilot-injection duration, dwell time, EGR, etc.

Preliminary multiple-injection conceptual model



Source: Rajasegar and Srna, SAE2022-01-0454

Highly - oxygenated fuels pose additional challenges due to different mixing properties – potentially requiring new engine calibrations

Many renewable fuels are oxygenated, have reduced heating value and significantly lower stoichiometric AFR than fossil diesel / HC fuels

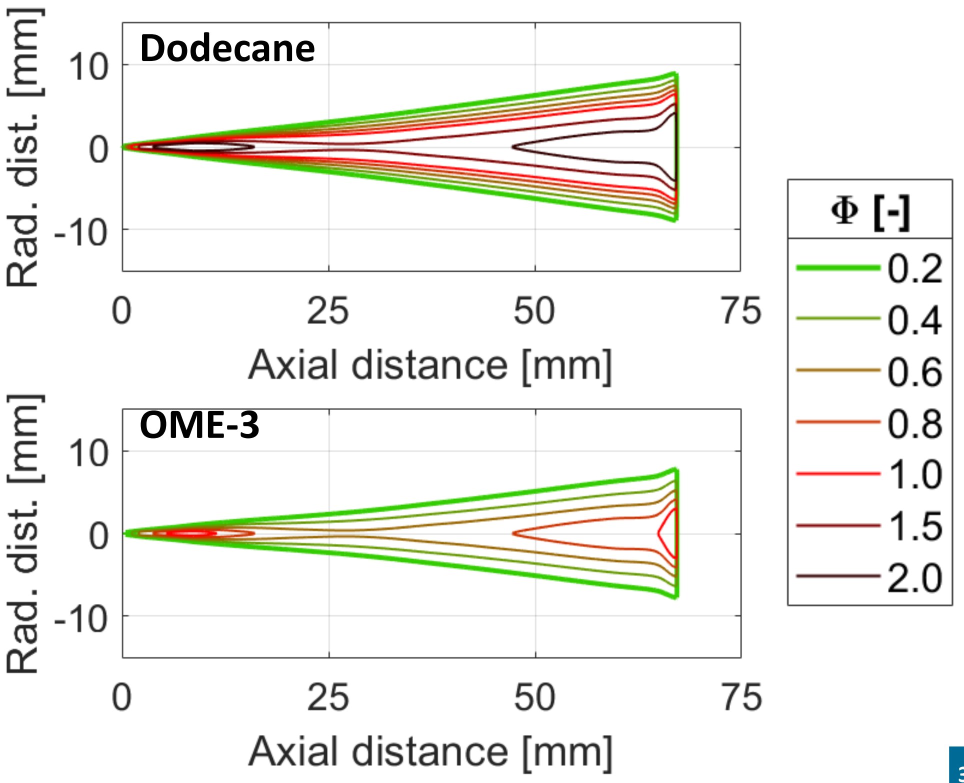
- Larger nozzle or injection pressure for the same engine power
- **Different engine optimization scope:**
  - Mitigation of engine noise and NOx
  - Soot formation likely not an issue
  - Operation at higher EGR rates

Improved understanding of oxygenates chemistry, ignition process and multiple-injection interactions can help faster engine adaptation to new fuels. Potential challenges:

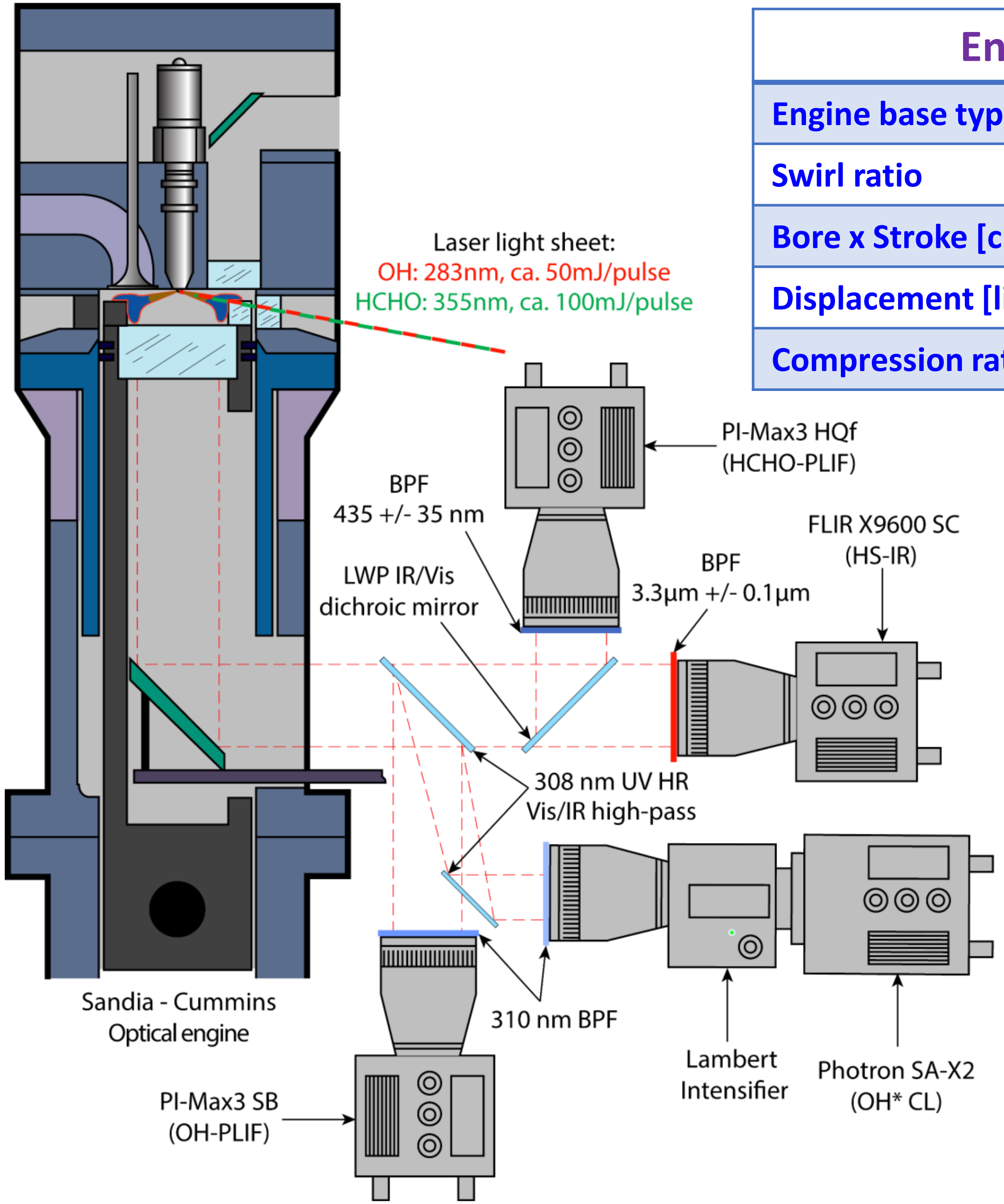
- Much faster mixture lean-out after the end-of-injection.
- Potential misfire and significant sources of UHC and formaldehyde from ultra-lean regions (too lean to autoignite)
- Larger amount of pilot-fuel might be needed to ensure reliable ignition.
- Ignition process differences due to the main injection experiencing different radicals and temperature distribution resulting from the pilot injection.

Fuel	AFR_{st}	Density [kg/m³]	LHV [MJ/kg]	Oxygen content
n-dodecane	15.0	750	44.1	0
OME 3-5 blend	~6	~1020	~20	~50%

Mixing field at 1.5ms ASOI (1ms injection)



Laser-based diagnostics and high-speed imaging in a heavy-duty, optical-engine to investigate the multiple-injection ignition process



Engine Specifications	
Engine base type	Cummins N-14, DI diesel
Swirl ratio	0.5
Bore x Stroke [cm]	13.97 x 15.24
Displacement [liters]	2.34
Compression ratio	10.75

Injector Specifications	
Injector type	Delphi DFI1.5, light-duty Solenoid actuated
Hole size	8 x 0.131 µm
Hole included angle	156°
Fuels	n-dodecane / OME_{3-5}

Two simultaneous slow-speed PLIF-based diagnostics:

- **CH_2O-PLIF:** Detection of 1^{st} stage ignition
  - 355 nm excitation (~100 mJ/pulse), detection in 400-470 nm band.
- **OH-PLIF:** Detection of 2^{nd} stage ignition spots and hot combustion products
  - 283 nm excitation (~50 mJ/pulse), detection at 310 nm.

Slow-speed diagnostics, only 1 frame/cycle. OH-PLIF and CH2O-PLIF detection quasi-simultaneous (1 µs separation)

High-speed imaging to support evaluation of PLIF diagnostics:

- **IR imaging:** Detection of unburnt and burnt fuel vapor
  - Jet penetration and evolution before ignition, 2 CAD/frame rate
- **OH* chemiluminescence:** Detection of flame and burnt zone
  - 0.25 CAD/frame rate, optical arrangement required viewing under a parallax of about 5°.

Test matrix include 12 injection cases, 4 charge conditions and two fuels

Fuels: OME 3-5 blend and n-dodecane as a reference fuel with nearly identical ID

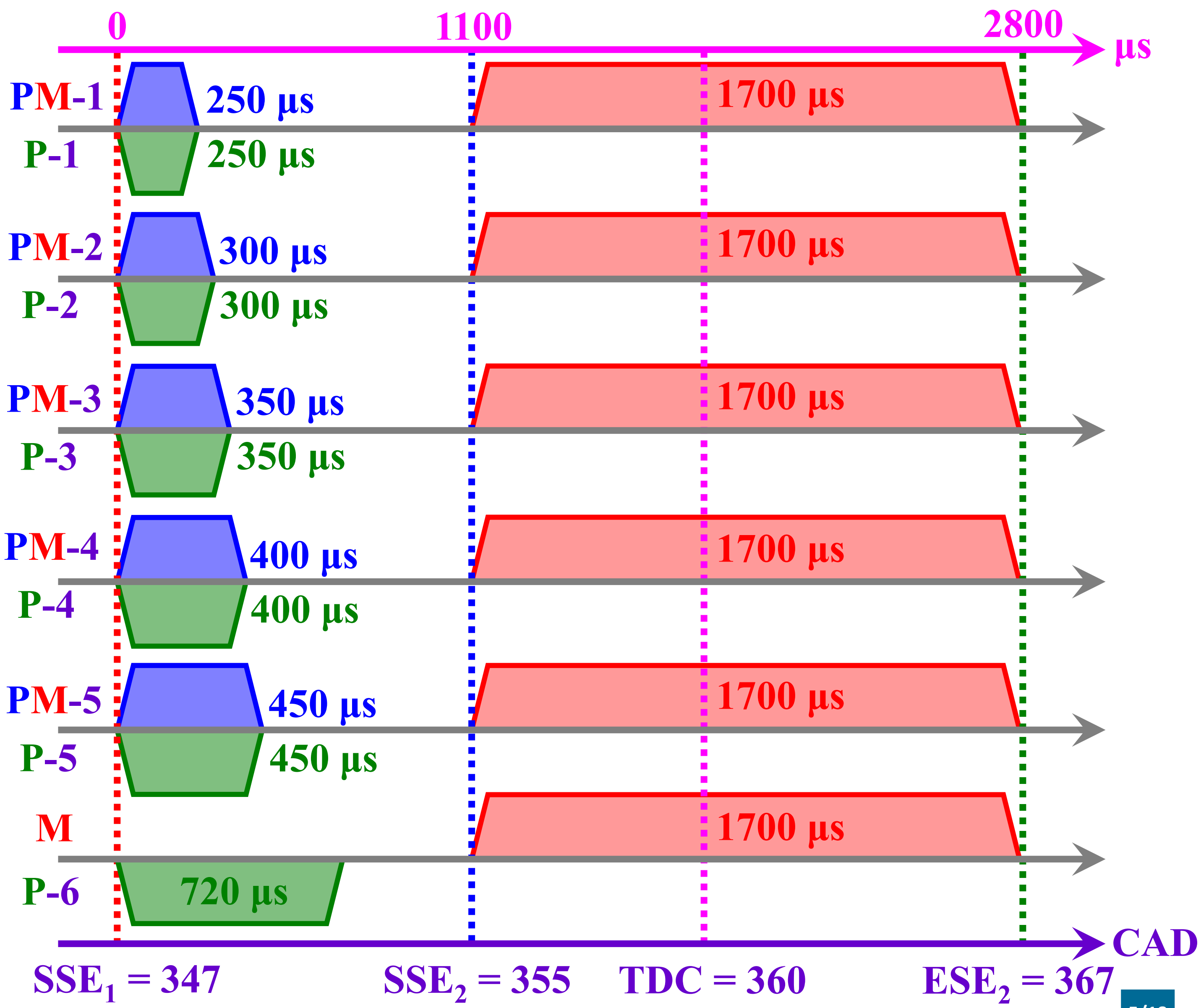
Charge: Two temperatures (intermediate and cold) and two EGR rates (18% and 10.5% O2) tested to reach a range of ignition delays and test the oxygen effects

Injections: 5 pilot-main schedules with different pilot durations. Pilot-only and main-only cases for reference.

Experimental Conditions Sweep

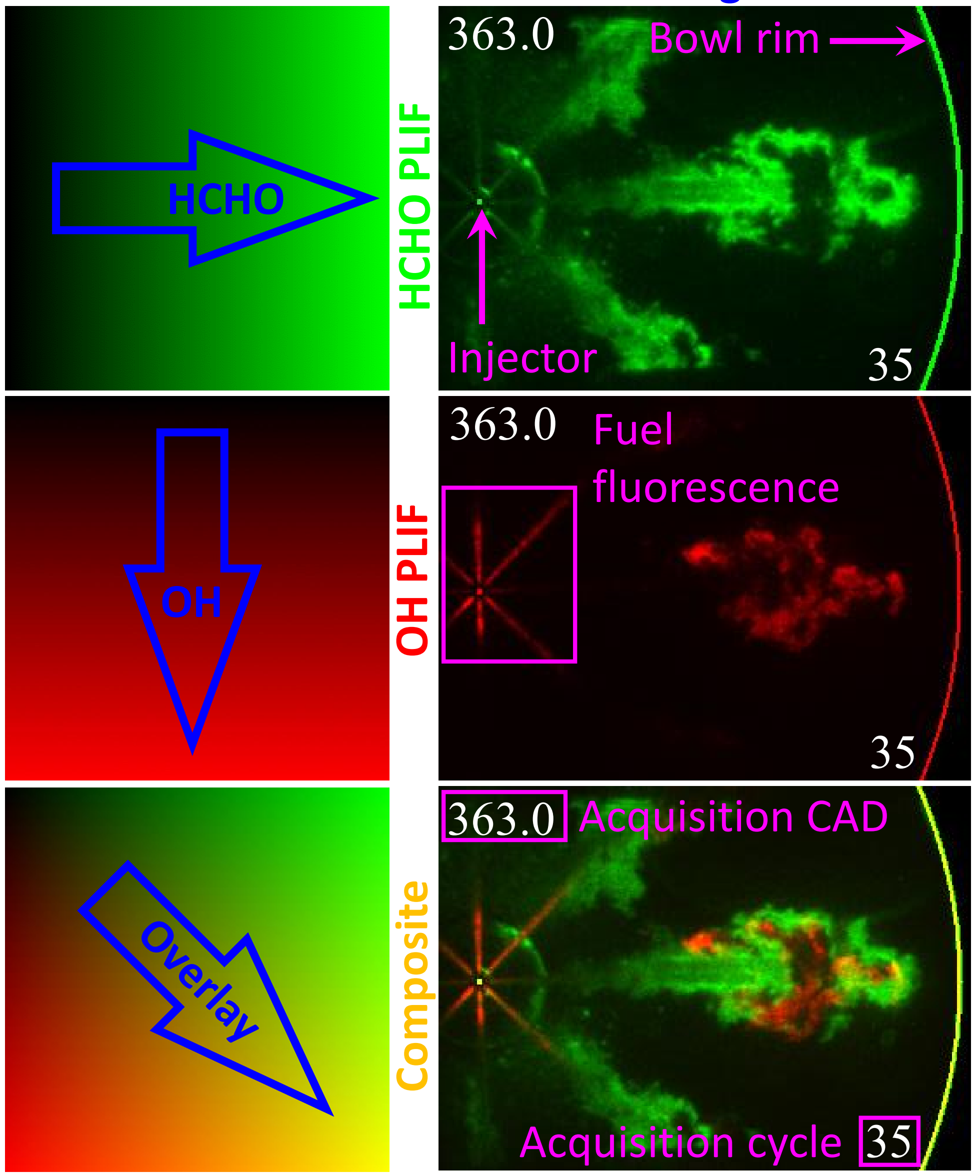
Parameters	1	2	3	4
Intake temp. (°C)	65	90	90	115
Intake press. (kPa)	155	165	165	175
EGR dil. O_2 (%)	18	18	10.5	10.5
Intake density (kg/m³)	~1.57	~1.57	~1.57	~1.57
TDC temp. (K)	767	824	824	880
TDC press. (bar)	37.8	40.2	40.2	42.7
TDC density (kg/m³)	16.88	16.88	16.88	16.88

Temp. effect at low EGR (1–2) | EGR effect at same temp. (2–3) | Temp. effect at high EGR (3–4)

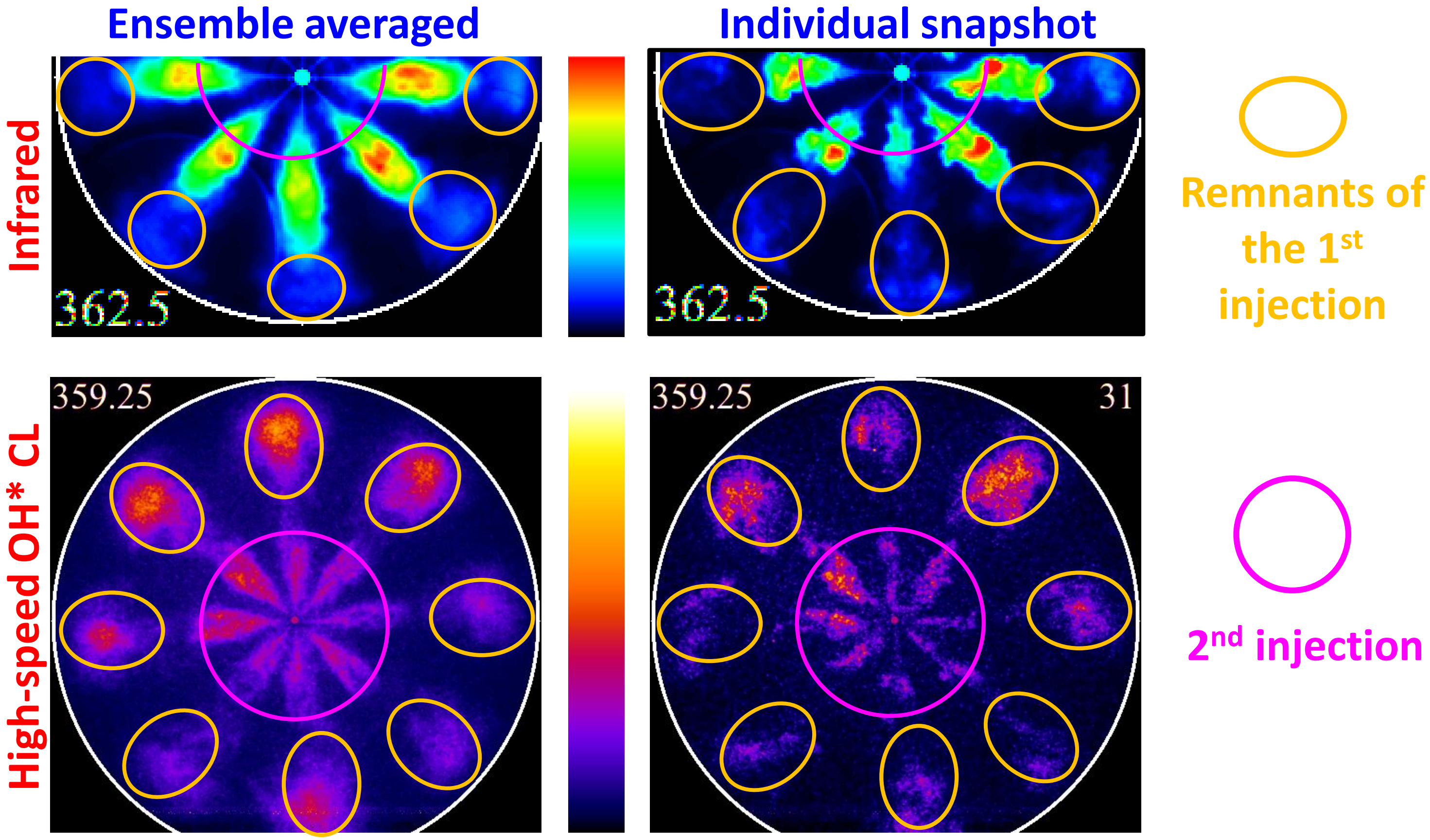


Composite images: HCHO (1st stage ignition) – OH (2nd stage ignition)
IR: unburnt fuel (C-H stretch) and burnt zone; OH* CL: Flame and burnt zone

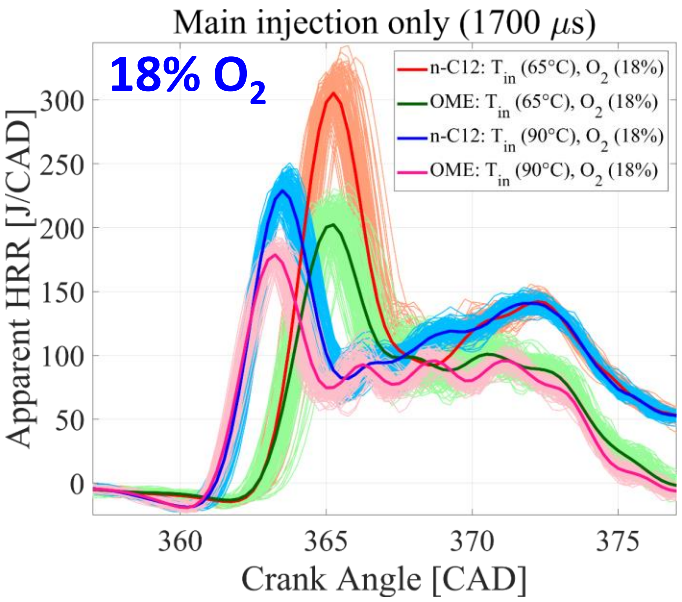
Composite snapshots consisting of OH-PLIF overlaid on HCHO-PLIF images

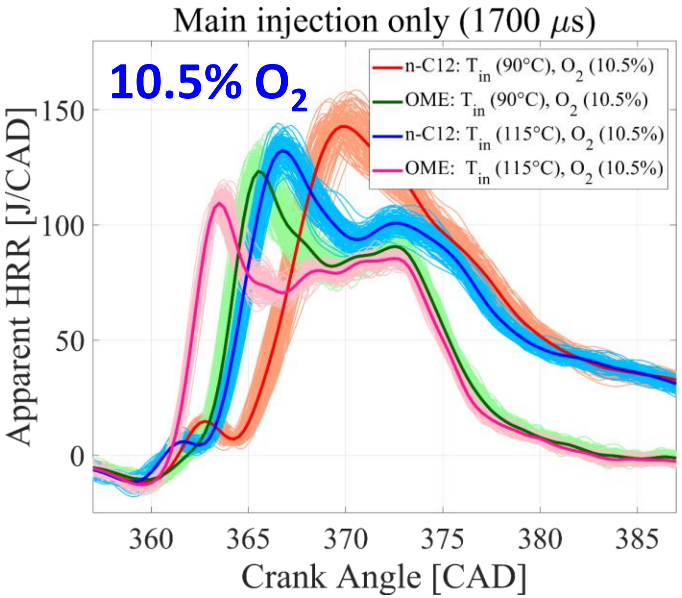


- PLIF images are *simultaneous but not sequential.*
- **N-C12:** **OH-PLIF** *signal loss/reduction* due to PAH/soot absorption/interference during later stages of combustion.
- **OME:** Decreased soot formation tendency. *Minimal interference* in **OH-PLIF** signal from PAH/soot.



OME: Peak premixed AHRR indicates rapid combustion. At low $[O_2]$, fuel-bound oxygen most likely compensates for reduced reactivity.





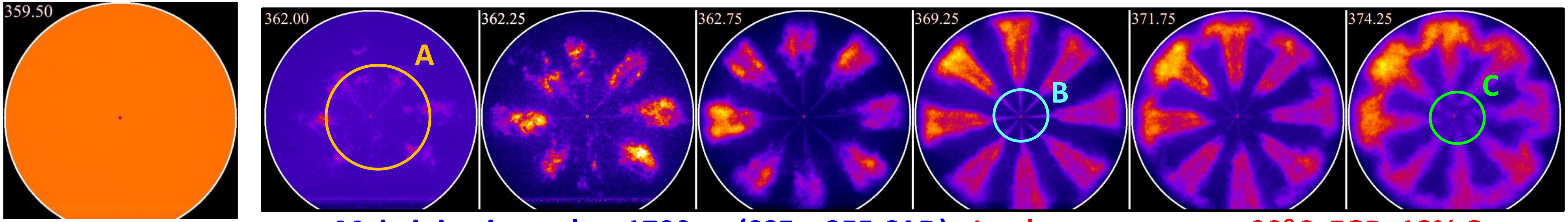
- At 18% O_2, irrespective of intake charge temperature, n-C12 and OME have nearly *identical ignition delays.* (~0.6 ms @ T_{in} = 65°C; ~0.4 ms @ T_{in} = 90°C)
- Despite the available mixing time, the *peak AHRR* during the premixed phase for OME *does not scale* as expected. (~ 67% - 77% of peak AHRR of n-dodecane)

$$\frac{(Peak\ AHRR)_{OME}}{(Peak\ AHRR)_{n-C12}} \sim \left[\frac{(\rho)_{OME}}{(\rho)_{n-C12}}\right]^{0.5}\left[\frac{(LHV)_{OME}}{(LHV)_{n-C12}}\right] \sim \left[\frac{1020}{750}\right]^{0.5}\left[\frac{20}{44.1}\right] \sim 0.53$$

- This indicates that OME may tend to undergo a *rapid "volumetric" burn.* More energy is quickly released in premixed phase potentially due to absence of overly rich zones.
- At 10.5% O_2, irrespective of intake charge temperature, there are distinctive differences in the AHRR.
  - Onset of cool-flame or 1st stage ignition remains comparable. (~0.4 ms)
  - However, n-C12 exhibits a prolonged 1st stage combustion with *longer dwell times* (~0.4 ms) until the onset of 2nd stage ignition, while no such prolonged dwell period is observable for OME.
  - Reduced $[O_2]$ lowers chemical reactivity ($ID \sim [O_2]^{-1}$) but in the case of OME, presence of *fuel-bound oxygen* most likely can compensate for this effect to some extent resulting in exacerbated differences in the onset of 2nd stage ignition between the two fuels. (Reaction kinetics study needed to confirm!)

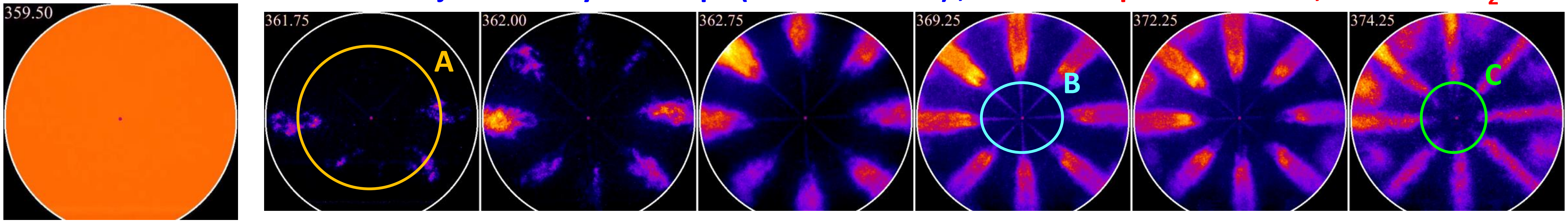
Near identical IDs @ 18% O_2 ; OME ignites further downstream with longer lift-off length & less apparent combustion-recession following EOI

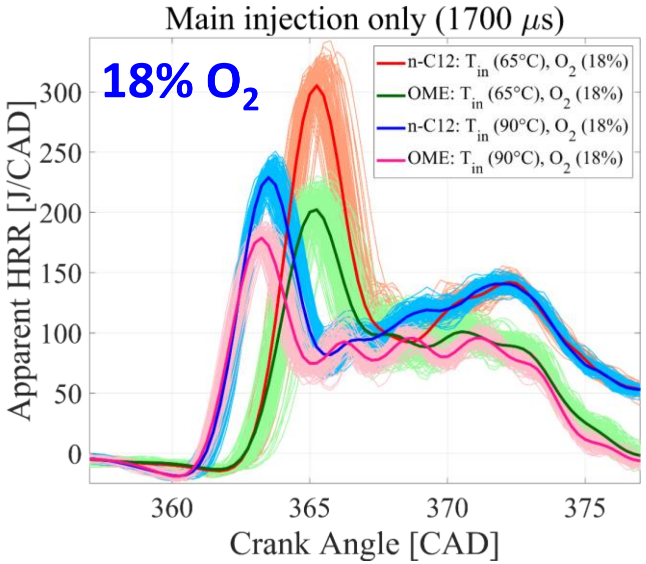
n-dodecane



Main injection only – 1700 µs (SSE = 355 CAD) ; Intake temperature: 90°C, EGR: 18% O_2

OME





Ensemble averaged snapshots of OH* chemiluminescence

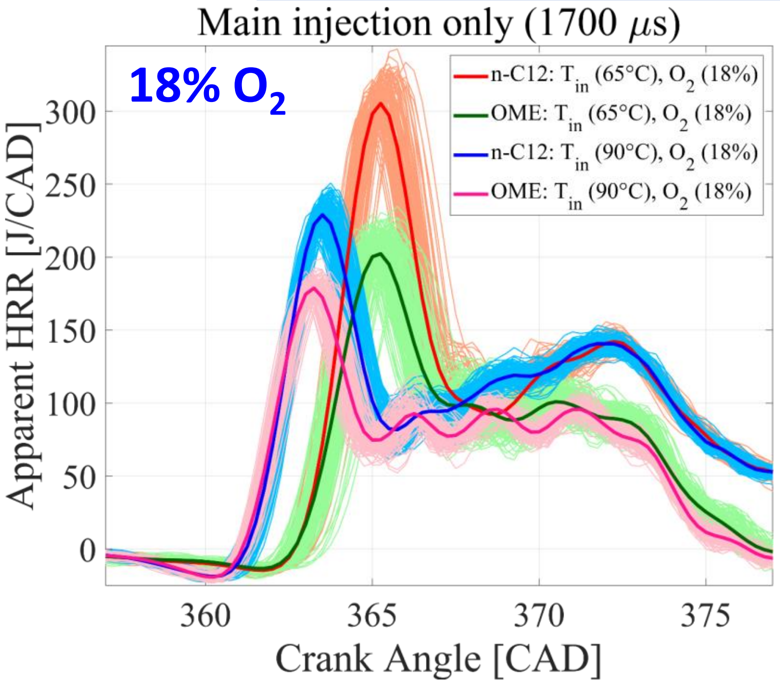
N-dodecane:

- A: Fuel-jets tend to ignite closer to the injector.
- B: Shorter lift-off length.
- C: Distinctive “combustion-recession” following EOI entrainment wave.

OME:

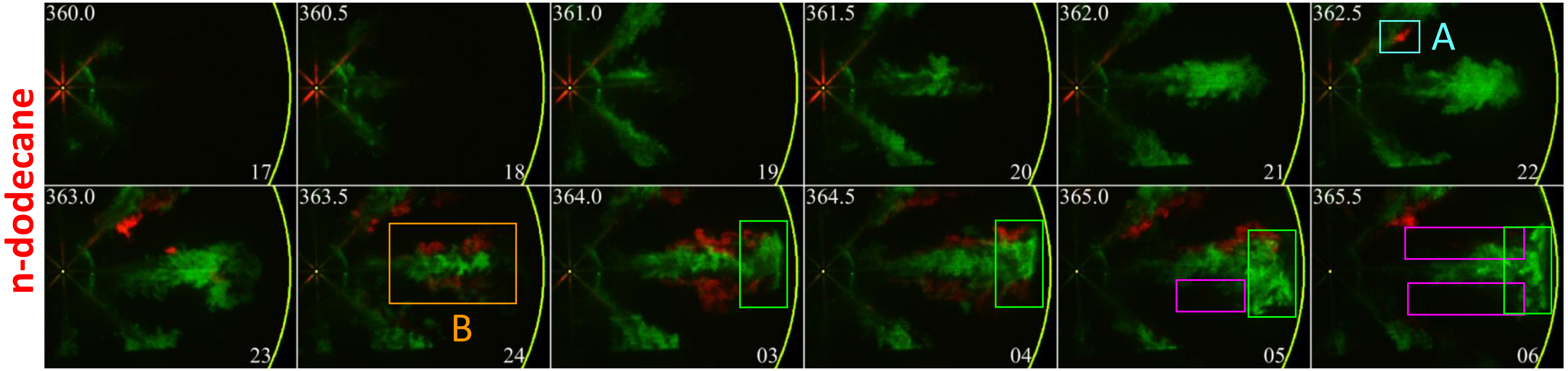
- A: Fuel-jets tend to ignite farther downstream of the injector.
- B: Relatively longer lift-off length.
- C: Less apparent “combustion-recession” following EOI entrainment wave.

OME: 2^{nd} stage ignition happens closer to the fuel-jet axis (differences in ϕ distribution) undergoing a volumetric combustion (inherent fuel-bound O_2)

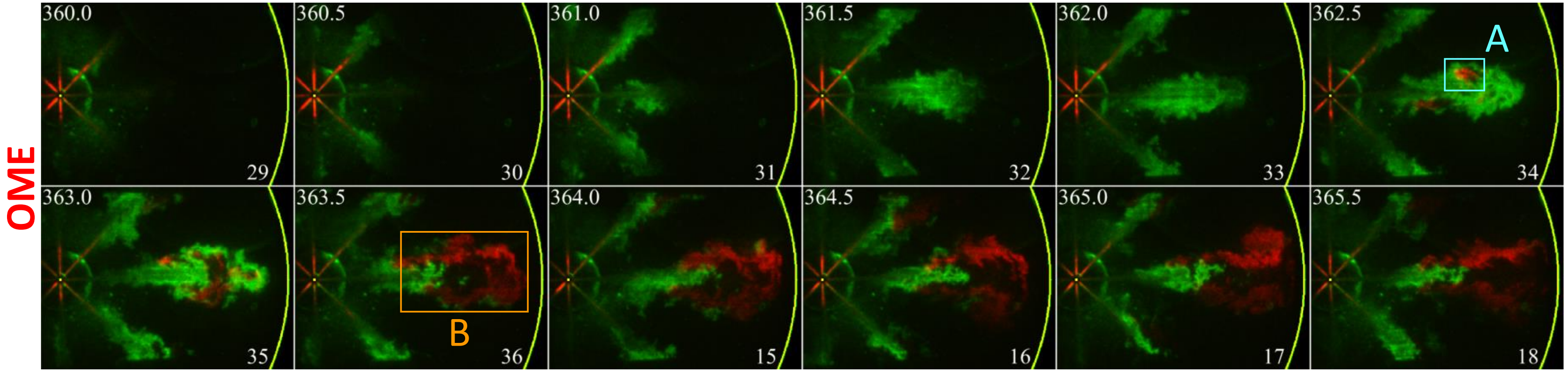


Regions of **OH-PLIF** *signal loss/reduction* due to PAH/soot absorption/interference. Changes in HCHO-PLIF sharpness and distribution.

Regions of possible discrepancy in HCHO-PLIF (near spray tip) due to possible PAH signal overlap following 2^{nd} stage ignition.



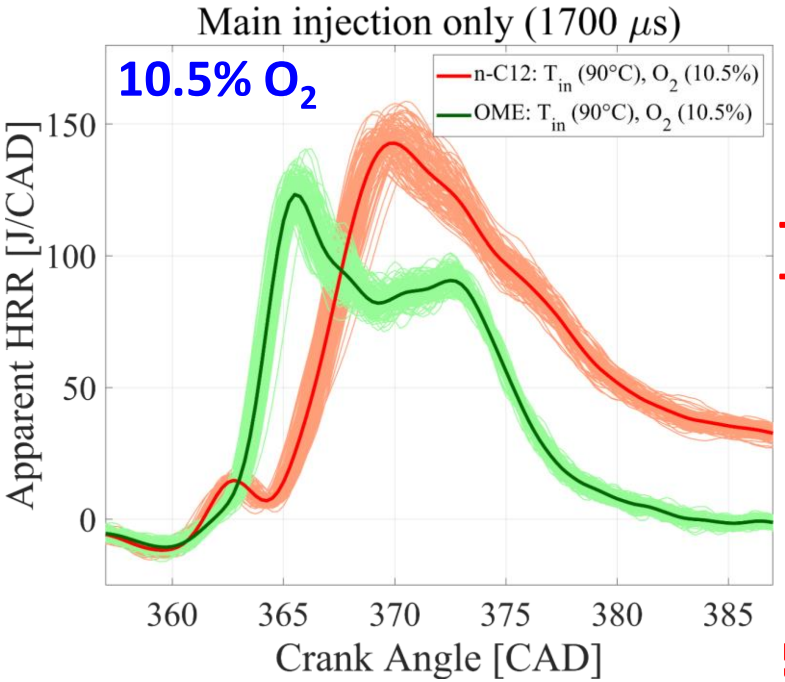
Main injection only – 1700 μs (SSE: 355 CAD) ; Intake temperature: 90°C, EGR: 18% O_2

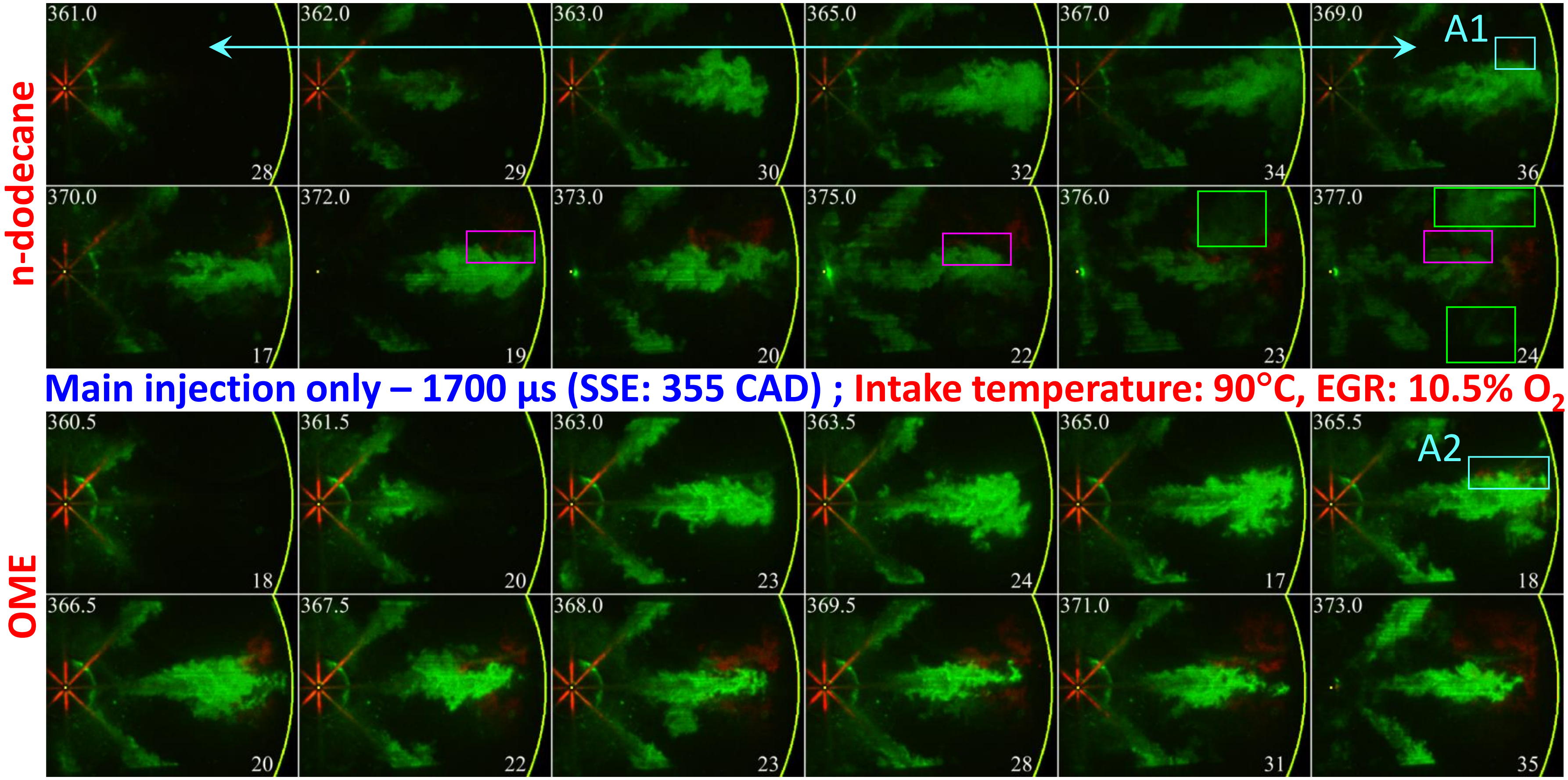


Composite snapshots consisting of OH-PLIF overlaid on HCHO-PLIF images

- At 18% O_2: Both fuels exhibit near *identical 1^{st} and 2^{nd} stage ignition delays* irrespective of intake charge temperature.
- **A:** Observable differences in the spatial location of 2^{nd} stage ignition. *n-C12: periphery of fuel-jet*, *OME: closer to the jet-axis.*
- **B:** OME tends to undergo more *volumetric combustion* resulting in higher peak AHRR i.e., does not scale with the LHV.

n-C12: ID ~ $[O_2]^{-1}$. Excessively long dwell time to 2nd stage ignition.
OME: Fuel-bound oxygen potentially compensates for reduced $[O_2]$.





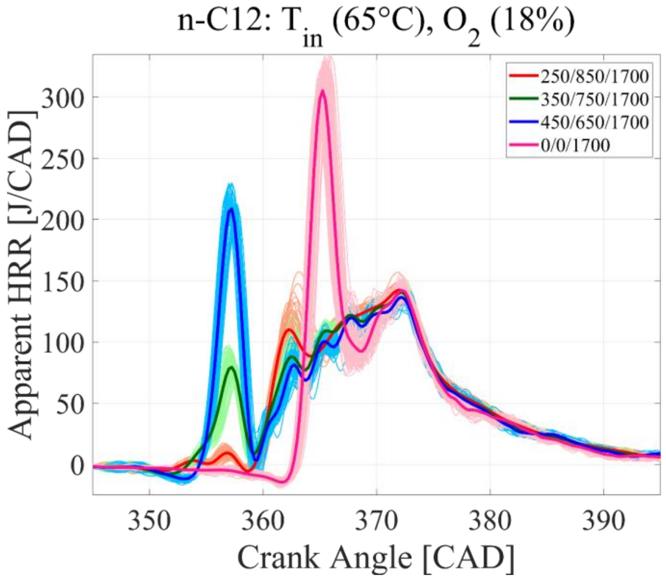
Composite snapshots consisting of OH-PLIF overlaid on HCHO-PLIF images

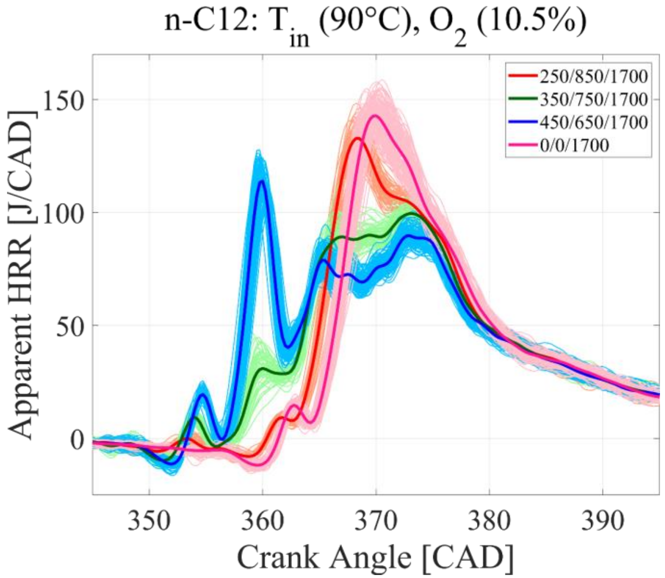
Regions of **OH-PLIF** *signal loss/reduction* due to PAH/soot absorption/interference. Changes in HCHO-PLIF sharpness and distribution.

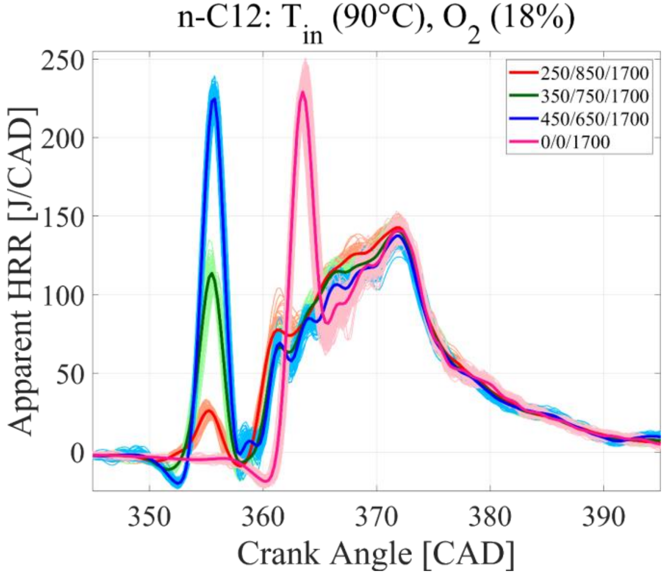
Regions of possible discrepancy in HCHO-PLIF (near spray tip) due to possible PAH signal overlap following 2nd stage ignition.

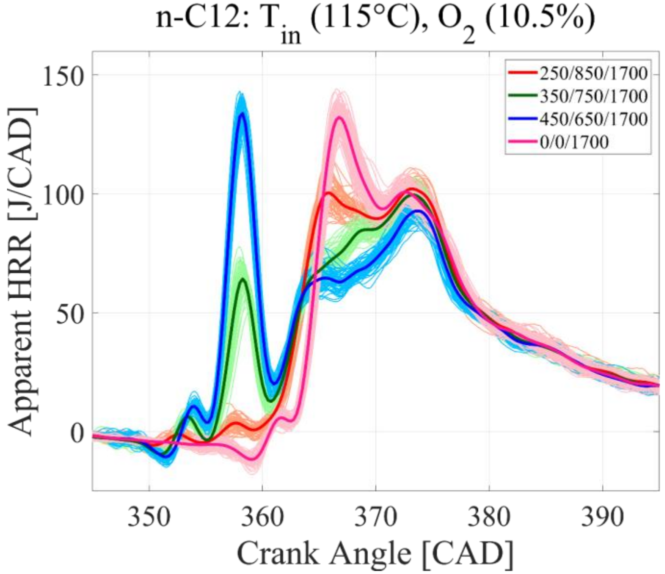
- At 10.5% O_2: The two fuels exhibit significant *differences in the 2nd stage ignition delays.*
- **A1:** *n-C12* exhibits a *prolonged 1st stage* combustion with *longer dwell time to 2nd stage ignition onset.* ID ~ $[O_2]^{-1}$
- **A2:** *Fuel-bound oxygen* in *OME* mostly likely compensates for reduced ambient $[O_2]$ *preventing excessively long dwell times* to onset of 2nd stage ignition. (Reaction kinetics study needed to confirm!)

At 18% O_2: Shortest pilot-injection can decrease ID and peak premixed AHRR. At 10.5% O_2: Effect of pilot is less pronounced due to decreased reactivity.









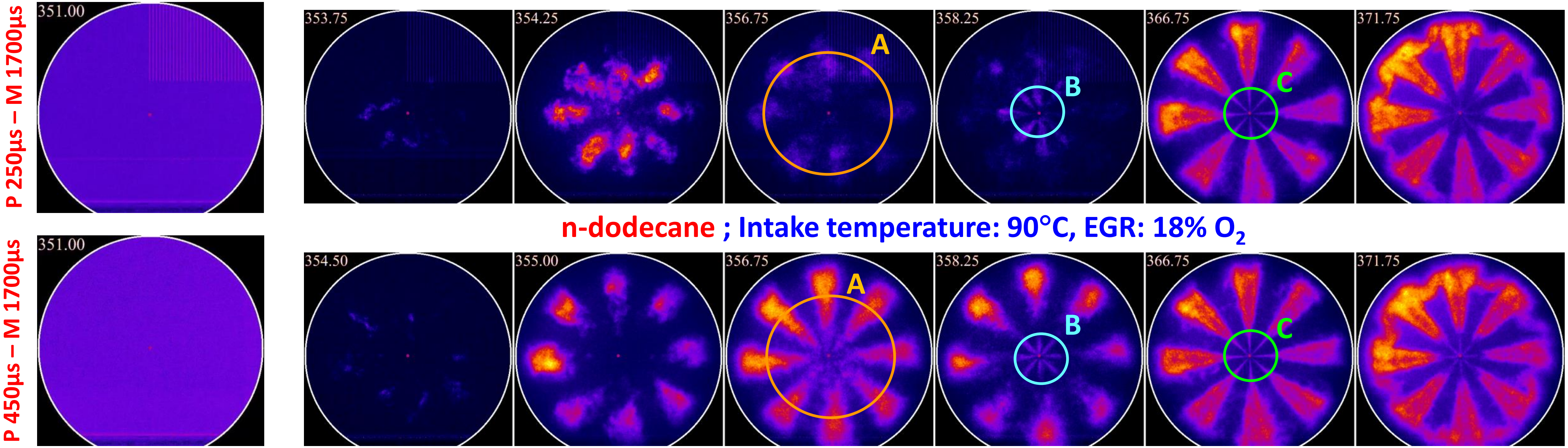
18% O_2

10.5% O_2

n-dodecane

- At **18% O_2**, the effect of pilot-injection is apparent and is almost *independent of the pilot duration* and the intake charge temperature.
  - ID is decreased by a factor of 2.5.
  - Peak premixed AHRR is decreased by a factor 3.
- At **10.5% O_2**, due to the reduced reactivity and increased ID, the effect of pilot-injection becomes *less apparent* with *pilot durations playing a key role*.
  - Shortest pilot can still decrease ID but with minimal effect on the peak premixed AHRR.
  - Longer pilots tends to have a more significant effect on decreasing ID and reducing peak premixed AHRR.

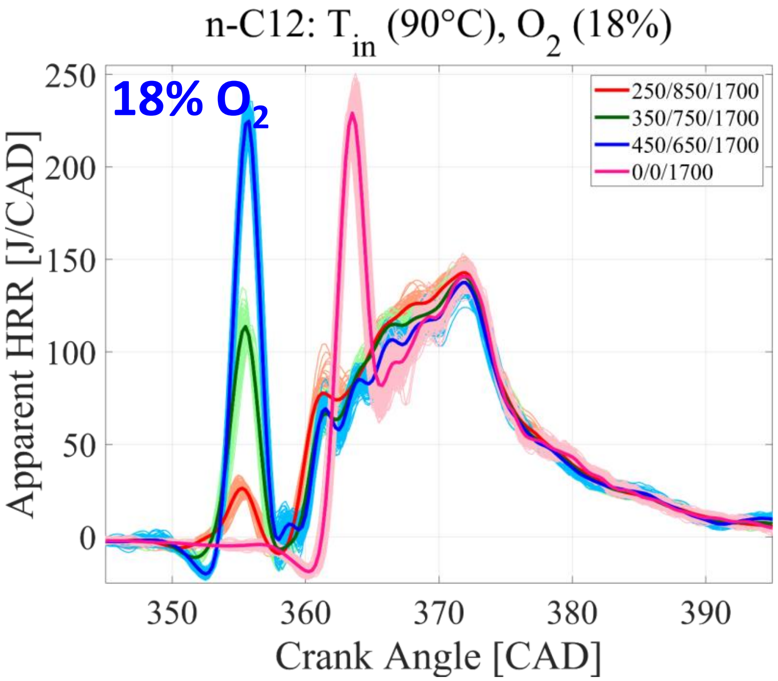
n-C12: High-temp. combustion products from the pilot ignites main-jet rapidly. Marginally shorter lift-off length can potentially lead to higher PAH/soot



Ensemble averaged snapshots of OH* chemiluminescence

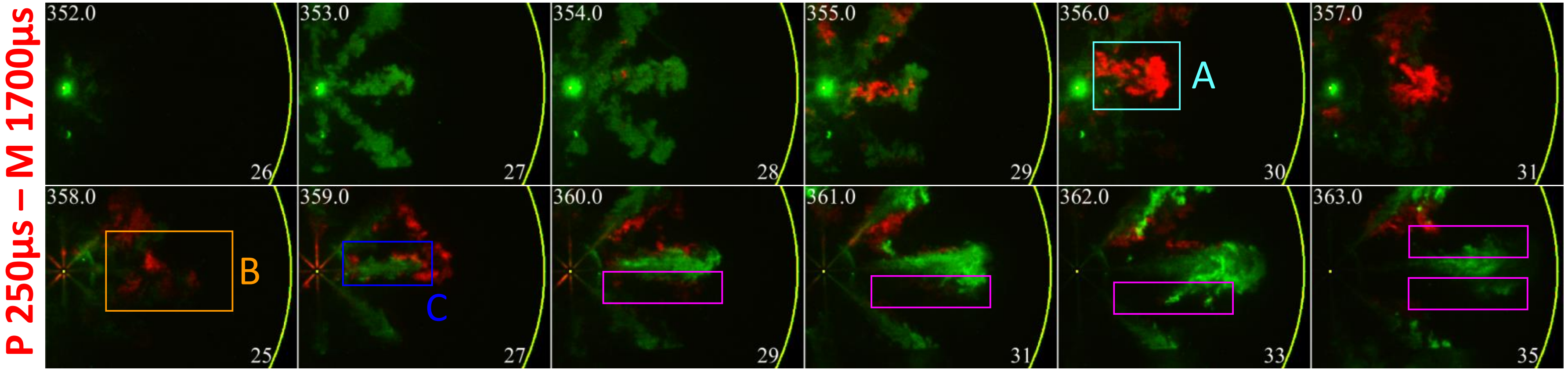
- **A:** High-temperature combustion products from the pilot are distributed throughout the combustion chamber. *Combustion-recession* following the pilot-EOI entrainment-wave *distributes the combustion products close to the injector.*
- **B:** Main-injection appears to *ignite rapidly* as it penetrates the high-temperature reactive environment.
- **C:** Lift-off length is *marginally shorter* when compared to the main-injection only case, i.e., ignition happens in fuel-rich region with reduced oxygen concentration (relative to ambient) leading to *exacerbated PAH and soot* formation in the main-injection.

n-C12: Main-jet rapidly ignites as it penetrates into an environment of high-temperature combustion products left behind by the pilot

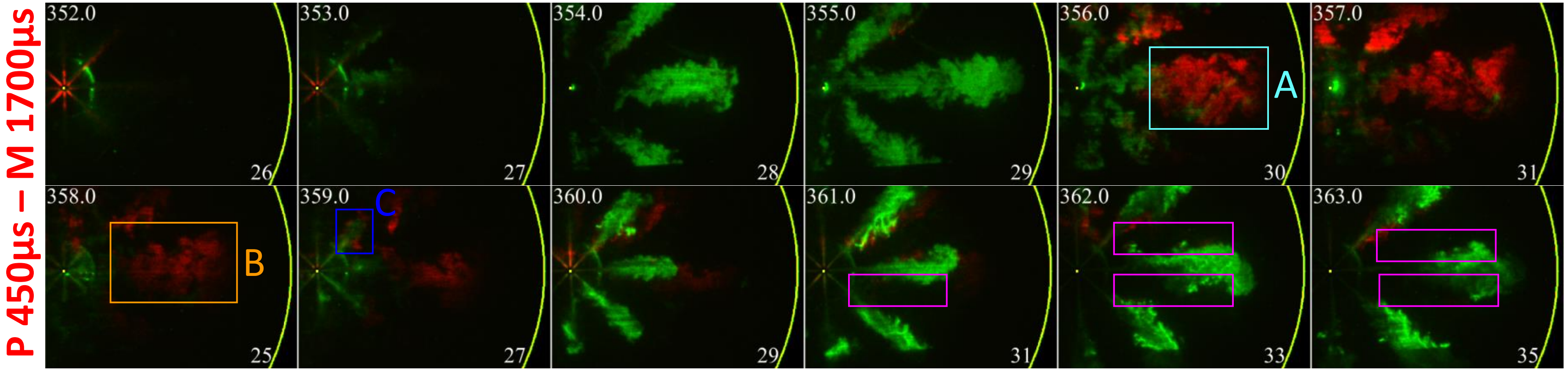


Regions of **OH-PLIF** *signal loss/reduction* due to PAH/soot absorption/interference. Changes in HCHO-PLIF sharpness and distribution.

Similar behavior to Skeen's high temperature (900 K) case



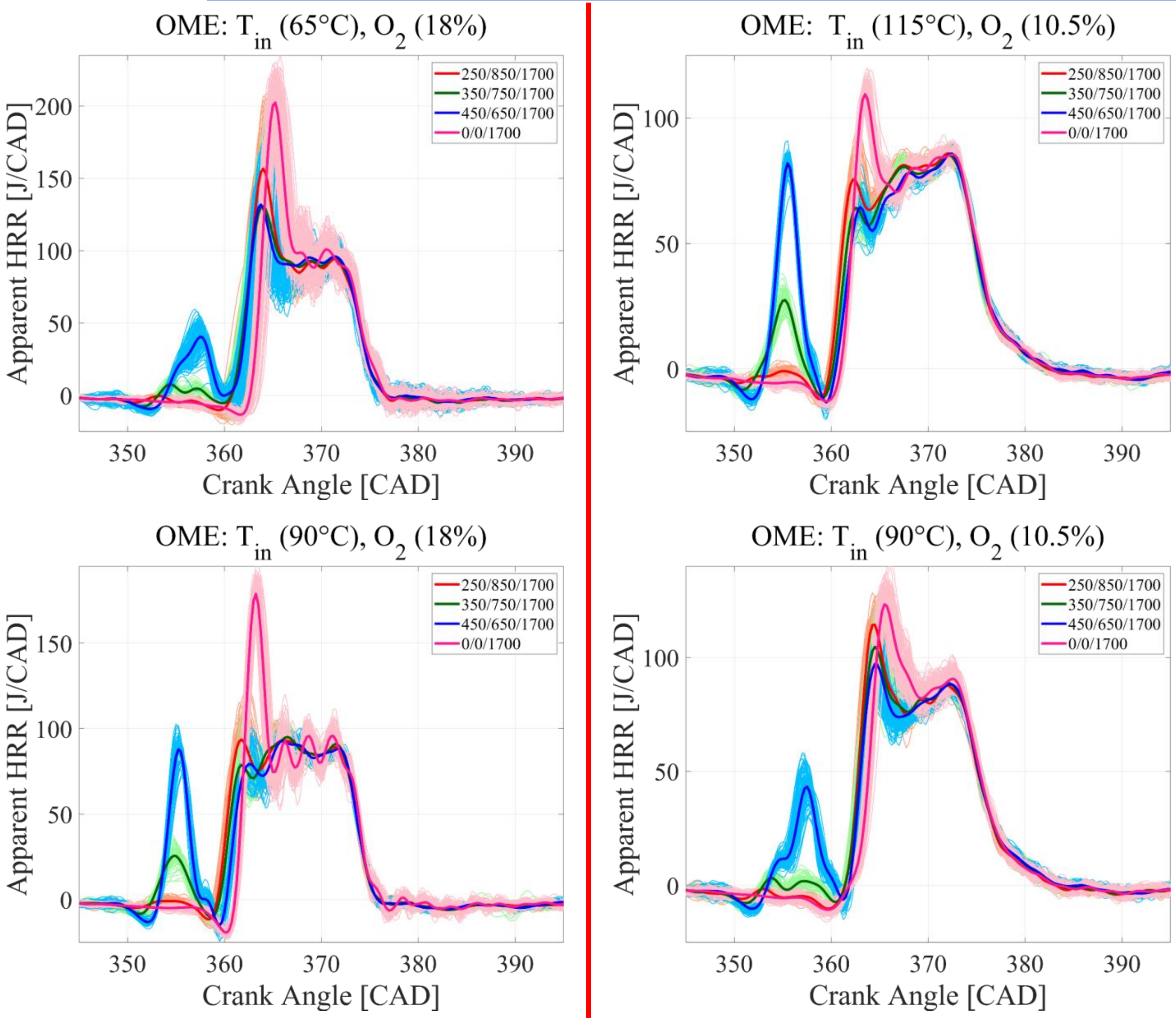
n-dodecane (SSE$_1$: 347 CAD, SSE$_2$: 355 CAD); Intake temperature: 90°C, EGR: 18% O_2



Composite snapshots consisting of OH-PLIF overlaid on HCHO-PLIF images

- **A:** Even the shortest pilot (250 µs) transitions into 2nd stage ignition producing substantial burnt high-temperatures zones.
- **B:** Main-injection penetrates into an environment of *high-temperature combustion products* following the "combustion-recession" event of the pilot-injection.
- **C:** The hot combustion products from the pilot facilitate *rapid (almost instantaneous) ignition* of the main-injection.

Effect of pilot-injection is less pronounced with ambient [O_2] not playing a significant role. Pilot has minimal effect on peak premixed AHRR.

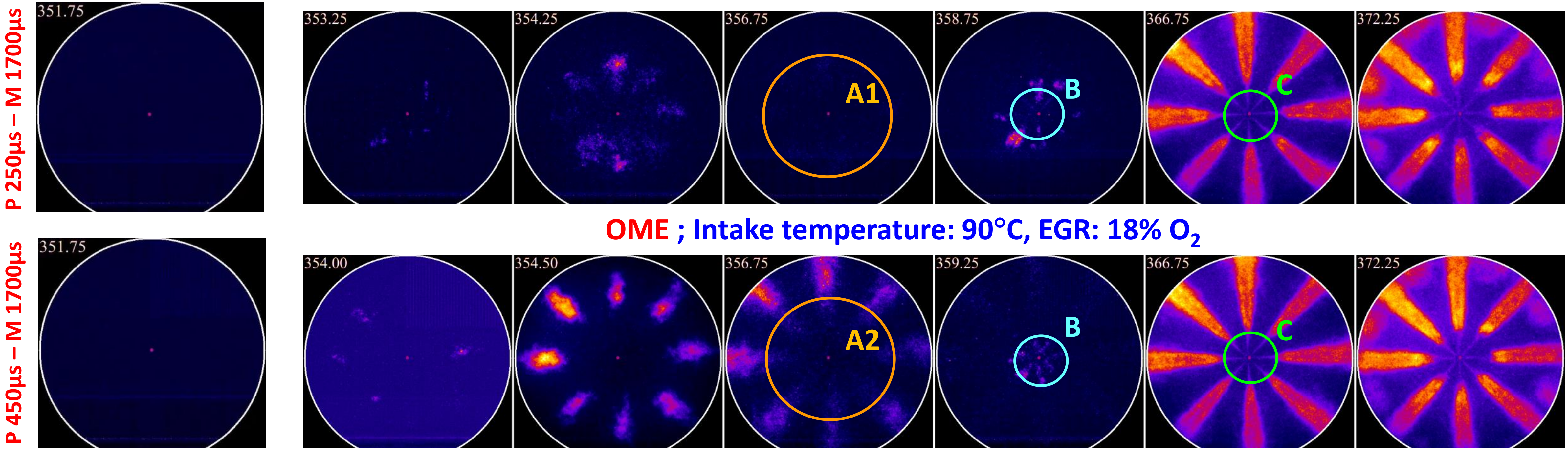


18% O_2 **10.5% O_2**

OME

- Unlike n-C12, the effect of pilot-injection is *less dependent on ambient oxygen concentration* and is more *governed by intake charge temperature.*
- ID of the main-injection decreases with increasing pilot durations.
- Unlike n-C12, the effect of pilot-injection on the *peak premixed AHRR* is *less pronounced* especially at lower intake temperatures.
- This can be attributed at least in part to the *fuel-bound oxygen* in OME contributing to its tendency undergo a *rapid volumetric burn* whereby the peak premixed AHRR is predominantly governed by the ID.

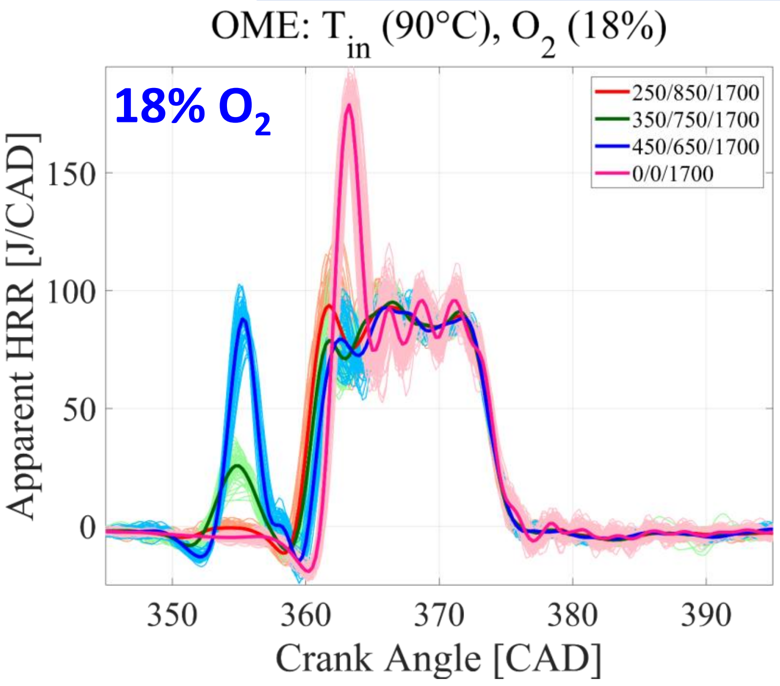
OME: Rapid excessive lean-out of pilot prevents completion of 2nd stage combustion. Mixing of main-jet with cool-flame products initiates ignition.

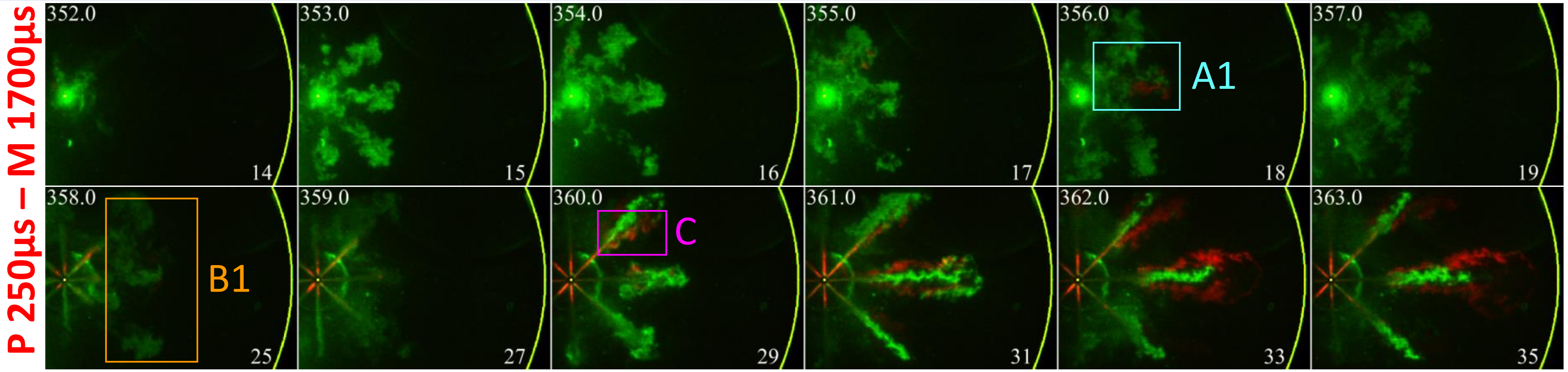


Ensemble averaged snapshots of OH* chemiluminescence

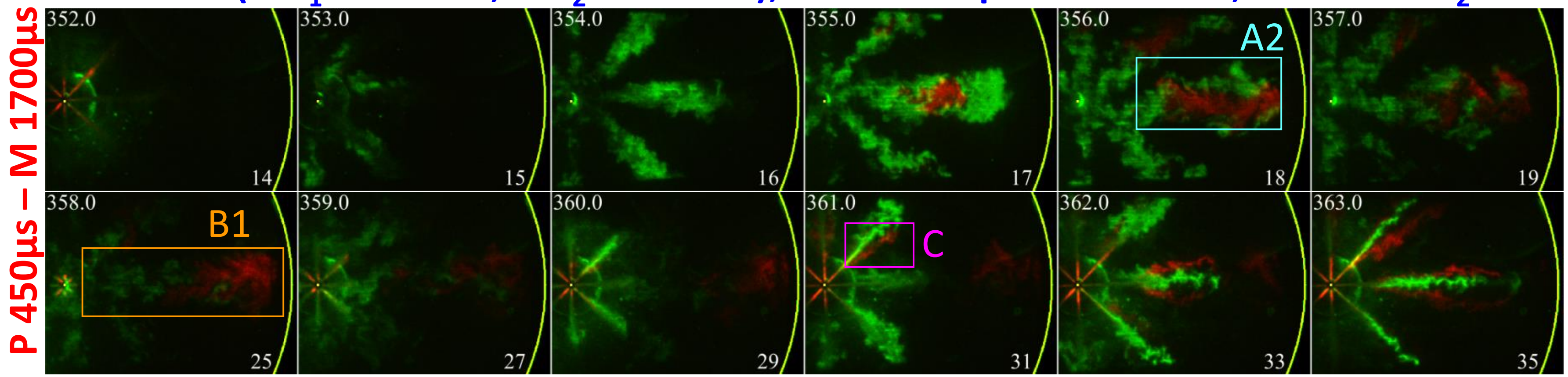
- **A1:** Shortest pilots (250 µs) shows only *isolated regions of 2nd stage ignition.* Mostly likely due to *rapid lean-out* caused by EOI-entrainment wave that reduces availability of most-reactive mixture fraction necessary for sustained high-temperature combustion. i.e., only the richest available mixtures autoignite.
- **A2:** Longer pilots (>350 µs) transition *partly into 2nd stage ignition.* But reduced combustion recession due to *rapid excessive lean-out* keeps high-temperature products fairly downstream of the injector.
- **B:** Main-injection penetrates and *mixes with the predominantly cool-flame combustion products* that eventually leads to ignition.
- **C:** Lift-off length is *distinctly shorter* when compared to the main-injection only case.

OME: Main-jet penetrates into an environment of predominantly cool-flame combustion products from the pilot that causes ignition lowering ID





OME (SSE$_1$: 347 CAD, SSE$_2$: 355 CAD); Intake temperature: 90°C, EGR: 18% O_2



Composite snapshots consisting of OH-PLIF overlaid on HCHO-PLIF images

Similar behavior to Skeen's intermediate temperature case (800 K)

- **A1:** Shortest pilot (250 µs) shows only *isolated regions of 2nd stage ignition* leaving behind mostly cool-flame products **(B1)**
- **A2:** Longer pilots (>350 µs) transition *partly into 2nd stage ignition* leaving behind a mix of hot and cool-flame combustion products **(B2)**
- **C:** Main-injection penetrates into an environment *composed predominantly of cool-flame combustion* products that causes ignition leading to reduced ignition delay.

Fuel-bound oxygen in OME can partly compensate for ambient [O_2]. OME reactivity primarily controlled by charge temperature.

Though n-dodecane and OME exhibit nearly identical ignition delays at high (18%) ambient oxygen concentration, there are some salient differences in the ignition and subsequent combustion process with OME.

- *Fuel-bound oxygen* in OME causes a potentially *rapid "volumetric" burn* resulting in higher-than-expected peak premixed AHRR. ***Combustion noise mitigation*** may be an important factor (more important than for conventional fuels) for consideration with OME operation.
- OME fuel-jets tend to ignite (i) further downstream of the injector (ii) closer to the jet-axis and exhibit (a) longer lift-off lengths and (b) less prominent combustion-recession following the end of injection entrainment-wave – *Differences in ϕ distribution*.
- Effect of *pilot-injection is less pronounced with OME*. For n-dodecane, the shortest pilot can reduce the ID and peak premixed AHRR of the main-injection by a factor of 2 and 3 respectively.
- For ***OME,*** the main-jet ignites as it penetrates and mixes with predominantly *cool-flame combustion products* in the near-injector region left behind by the rapidly leaning out pilot. For ***n-dodecane,*** the main-jet rapidly ignites as it penetrates into an environment of primarily *high-temperature combustion products* left behind by the pilot in the near-injector region.

At low (10.5%) ambient oxygen concentration, fuel-bound oxygen in OME can partly compensate for decreased reactivity, this leads to exacerbated differences in onset of 2nd stage ignition when compared n-dodecane which experiences prolonged dwell times.

Since fuel-bound oxygen in OME can partly compensate for reduced ambient oxygen concentration, reactivity is predominantly controlled by charge temperature unlike in n-dodecane where oxygen concentration plays a primarily role with charge temperature playing a secondary role.

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- Dr. Paul Miles, CRF Sandia – Manager (08362)
- Kyra Schmidt, CRF Sandia – Technologist

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Thank you !

Questions?

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