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Effect of Spray Collapse on Mixture Preparation and Combustion Characteristics of a Spark-Ignition Heavy-Duty Diesel Optical Engine Fueled with Direct-Injected Liquefied Petroleum Gas (LPG)

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Sandia National Laboratories

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Abstract

Liquid Petroleum Gas (LPG), as a common alternative fuel for internal combustion engines is currently widespread in use for fleet vehicles. However, a current majority of the LPG-fueled engines uses port-fuel injection that offers lower power density when compared to a gasoline engine of equivalent displacement volume. This is due to the lower molecular weight of LPG components that displace more air in the intake charge. LPG direct-injection during the closed-valve portion of the cycle can avoid displacement of intake air and can thereby help achieve comparable gasoline-engine power densities. However, under certain engine operating conditions, direct-injection sprays can collapse and lead to sub-optimal fuel-air mixing, wall-wetting, incomplete combustion, and increased pollutant emissions. Direct-injection LPG, owing to its thermo-physical properties is more prone to spray collapse than gasoline sprays. However, the impact of spray collapse for high-volatility LPG on mixture preparation and subsequent combustion is not fully understood. To this end, direct-injection, laser-spark ignition experiments using propane as a surrogate for LPG under lean and stoichiometric engine operating conditions were carried out in an optically accessible, single cylinder, heavy-duty, diesel engine. A quick-switching parallel propane and iso-octane fuel system allows for easy comparison between the two fuels. Fuel temperature, operating equivalence ratio and injection timing are varied for a parametric study. In addition to combustion characterization using conventional cylinder pressure measurements, optical diagnostics are employed. These include infrared (IR) imaging for quantifying fuel-air mixture homogeneity and high-speed natural luminosity imaging for tracking the spatial and temporal progression of combustion. Imaging of infrared emission from compression-heated fuel does not reveal any significant differences in the signal distribution between collapsing and non-collapsing sprays at the spark timing. Irrespective of coolant temperatures, early injection timing resulted in a homogeneous mixture that lead to repeatable flame evolution with minimal cycle-to-cycle variability for both LPG and iso-octane. However, late injection timing resulted in mixture inhomogeneity and non-isotropic turbulence distribution. Under lean operation with late injection timing, LPG combustion is shown to benefit from a more favorable mixture distribution and flow properties induced by spray collapse. On the other hand, identical operating conditions proved to be detrimental for iso-octane combustion caused by likely distribution of lean mixtures near the spark location that negatively impact initial flame kernel growth leading to increased cycle-to-cycle variability.

Reduced cost of ownership of MD/HD trucks utilizing SI engines combined with LPG fuel

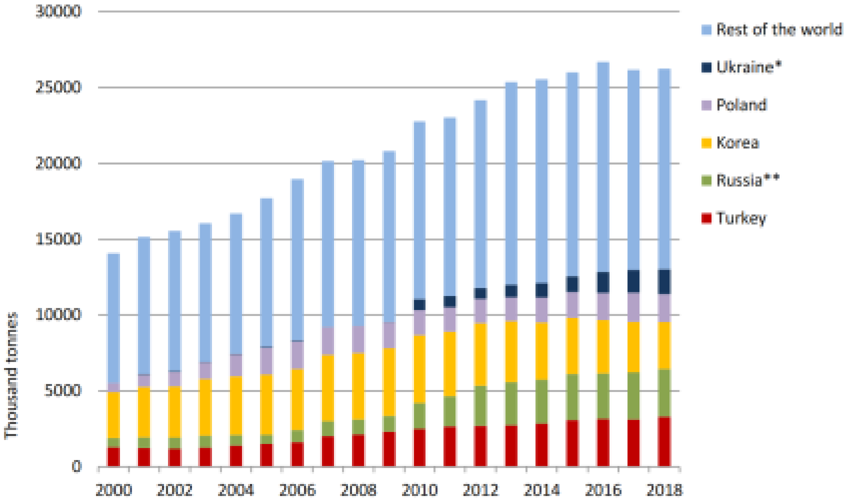
Renewed interest in SI-engines and SI-fuels applications in MD and HD vehicle classes

- Reduced cost of ownership: simplified engine design, reduced aftertreatment system complexity, lower cost of fuel
- Advanced SI combustion technology: increased SI engine efficiency, power output, reduced emissions
- LPG is an abundant domestic resource that has potential for lower cost than gasoline or diesel fuels

Properties of LPG (nearly 100% propane on US market)

- High RON and MON values (propane AKI=105)
- Comparable flame speeds to other HCs
- High vapor pressure: about 10bar at room temperature
- Less complex storage and transport compared to natural gas or hydrogen

Global consumption of LPG as transportation fuel



Source: WLPGA report: Autogas incentive policies 2019

Developing countries the main driver of demand:

- Only about 1.5% of road transport energy consumption
- Outdated vehicle fleet, emissions benefits
- Domestic resource and tax incentives

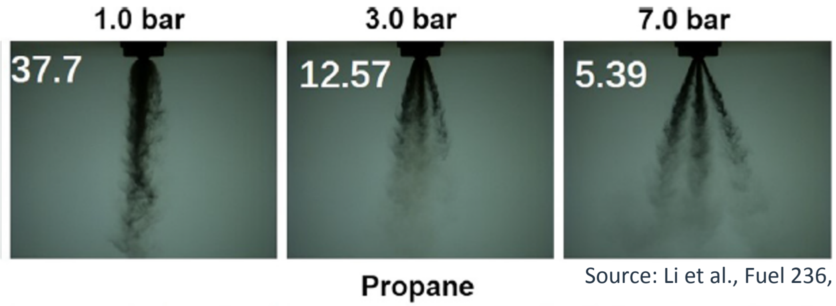
LPG flash boiling and spray collapse a likely barrier for wider adoption of LPG in SI engines – inadequate science base

LPG applications in MD/HD class vehicles are presently a niche application

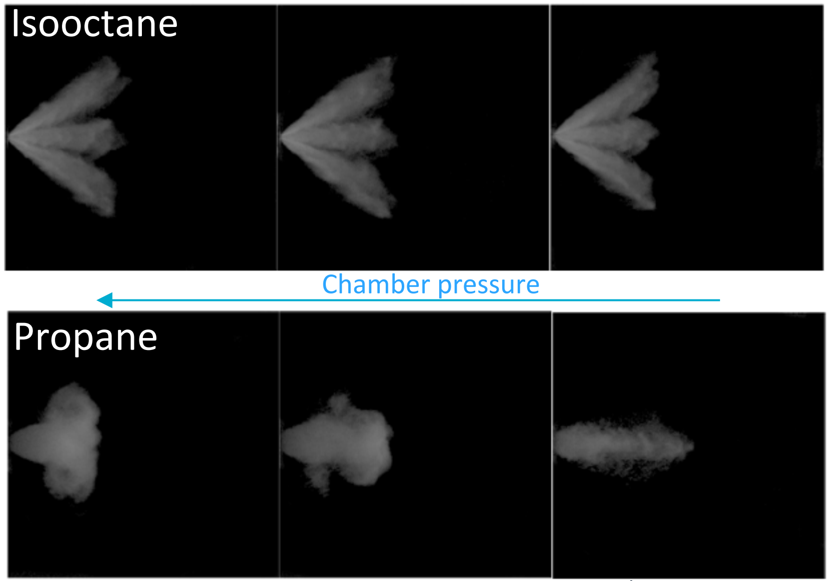
- SI MD/HD engines are an emerging technology
- Primarily, retrofits of light-duty gasoline engines
- Inadequate science base for LPG injection/combustion
- Compatibility of LPG with advanced gasoline SI engines is likely to be key to wider market penetration

Main barrier – mixture preparation

- Modern SI engines operate with tailored fuel stratification
- LPG has a strong tendency to flash boil
  - Vapor pressure at room temperature ~10 bar
- Spray collapse from multi-hole injector changes the engine fuel distribution and flow-field
  - ➢ Inferior performance of LPG fueled engine?
  - ➢ Aftertreatment system compatibility?
  - ➢ No data available on the effect of LPG spray collapse on subsequent combustion



Source: Li et al., Fuel 236, 2019



Source: Lacey et al., SAE 2016-01-0842

What is the importance of LPG spray collapse for mixture preparation in HD engine – well-mixed and stratified operation

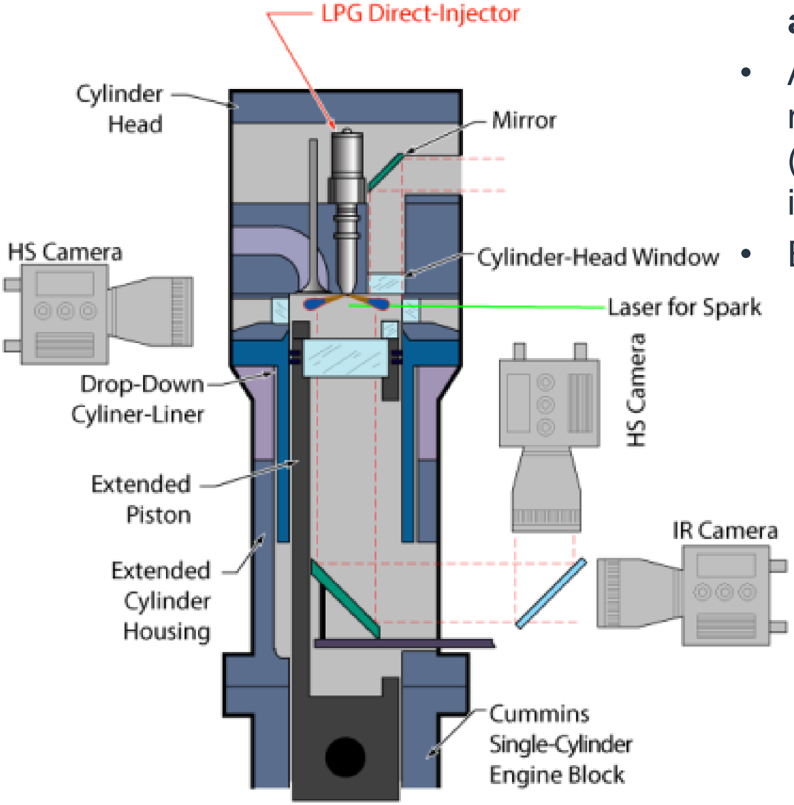
Outline

- **Introduction**
- **Experimental configuration**
  - LPG DI SI engine
  - Visualization of spray and flame evolution
  - Main experimental variations
- **Results:**
  - Spray evolution with LPG and iso-octane
  - Engine thermodynamic performance
  - Flame evolution and cyclic variability
  - Differences in fuel mixing
- **Summary and remaining barriers**

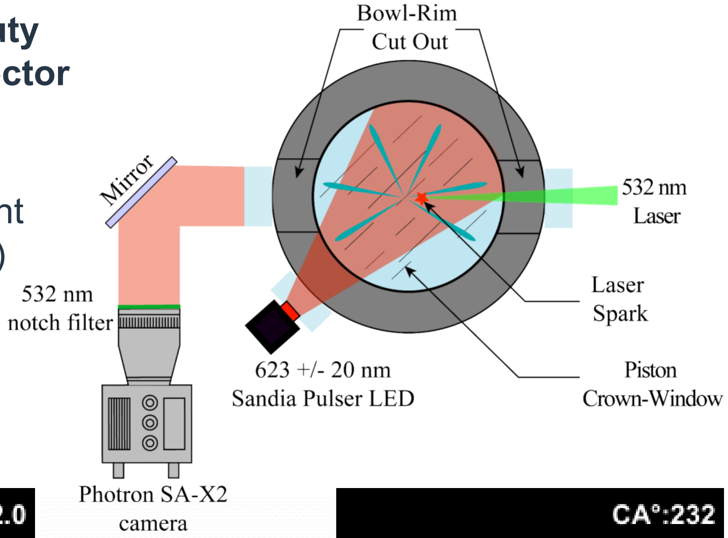
Key questions:

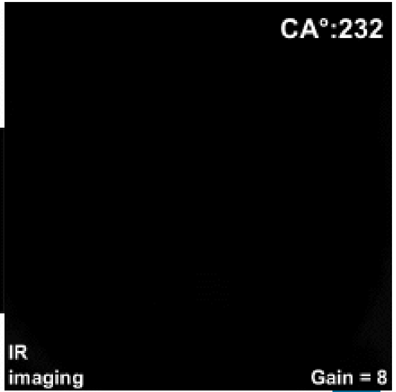
- **Can an asymmetric 6-hole injector prevent LPG spray collapse**
- **How does spray collapse influence mixture formation and flame evolution**
  - Homogeneous mixture formation using early fuel injection
  - Stratified mixture using late injection
  - Stoichiometric and fuel-lean operation
- **Compatibility of gasoline DISI spray targeting with LPG**
- **Future research directions for DISI heavy-duty engines**

Side and bottom visualization of flame natural luminosity and spray (Mie scattering); bottom-view IR imaging of compressed fuel



- **Bosch HDEV-5 light-duty asymmetric 6-hole injector**
- Asymmetric hole better resists spray collapse (space for air entrainment into the inter-spray area)
- Engine CR=10.3





Engine operating condition matrix sweeps start and duration of injection, global equiv. ratio and coolant (fuel) temperature

Variations:

- Fuel: propane and iso-octane as LPG and gasoline surrogates
- **Coolant temperature controls the fuel temperature**
- Global equivalence ratio
- Injection timing
  - Early injection - conditions correspond to ECN spray G3
  - Late injection – conditions at EOI correspond to ECN spray G
  - Injections are relatively long (injector flow limitation)
    - 15-26 ms DSE for LPG
    - 12-20 ms DSE for octane
    - Up to 100 CAD @ 600 RPM

Experimental Conditions	
Intake Temperature [C]	60
Intake Pressure [bar]	1
Intake O_2 [%]	21
Engine Speed [RPM]	600
Spark timing [°CA]	350

Early timing: ECN Spray G3

Late timing: ECN Spray G at EOI

Fuel	Coolant / Oil	EQR ϕ	Injection Timing
LPG (Propane)	Cold (30 °C)	1.0	Early / Late
		0.7	Early / Mid / Late
	Hot (90 °C)	1.0	Early / Late
		0.7	Early / Mid / Late
Iso-Octane	Cold (30 °C)	1.0	Early / Late
		0.7	Early / Mid / Late
Early: SSE = 60 CAD; Mid: SSE ≈ 120 CAD; Late: ESE = 311 CAD			

SSE: Start of Solenoid Energizing; ESE: End of Solenoid Energizing; DSE: Duration of Solenoid Energizing

LPG spray fully collapses during early injection while iso-octane sprays do not show any signs of collapse

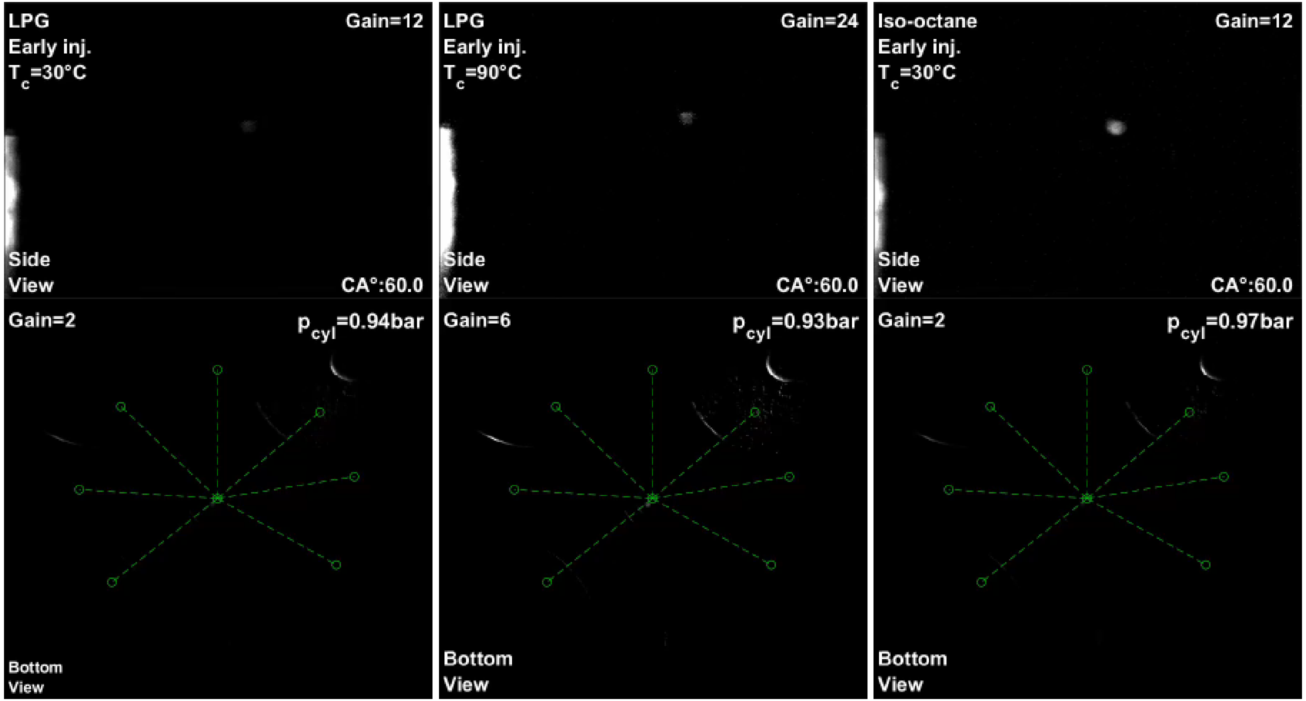
LPG spray

- LPG spray fully collapsed throughout the injection duration
- Initial collapse within 1 CAD after SOI
- Weaker Mie-scattering signal at hot coolant conditions – faster evaporation
- Narrow spray angle

Iso-octane (identical injector)

- Wider spray angle
- Individual sprays are not clearly distinguishable
- No spray collapse

LPG, cold (T_c=30C) | LPG, hot (T_c=90C) | Iso-octane, cold(T_c=30C)



- Top part of image: side view of the spray
- Bottom part: simultaneous bottom-view of the spray
- Green lines separate 6 nozzle zones

During transient late injection, the LPG spray overcomes collapse when cylinder pressure > 3bar; No collapse of iso-octane sprays

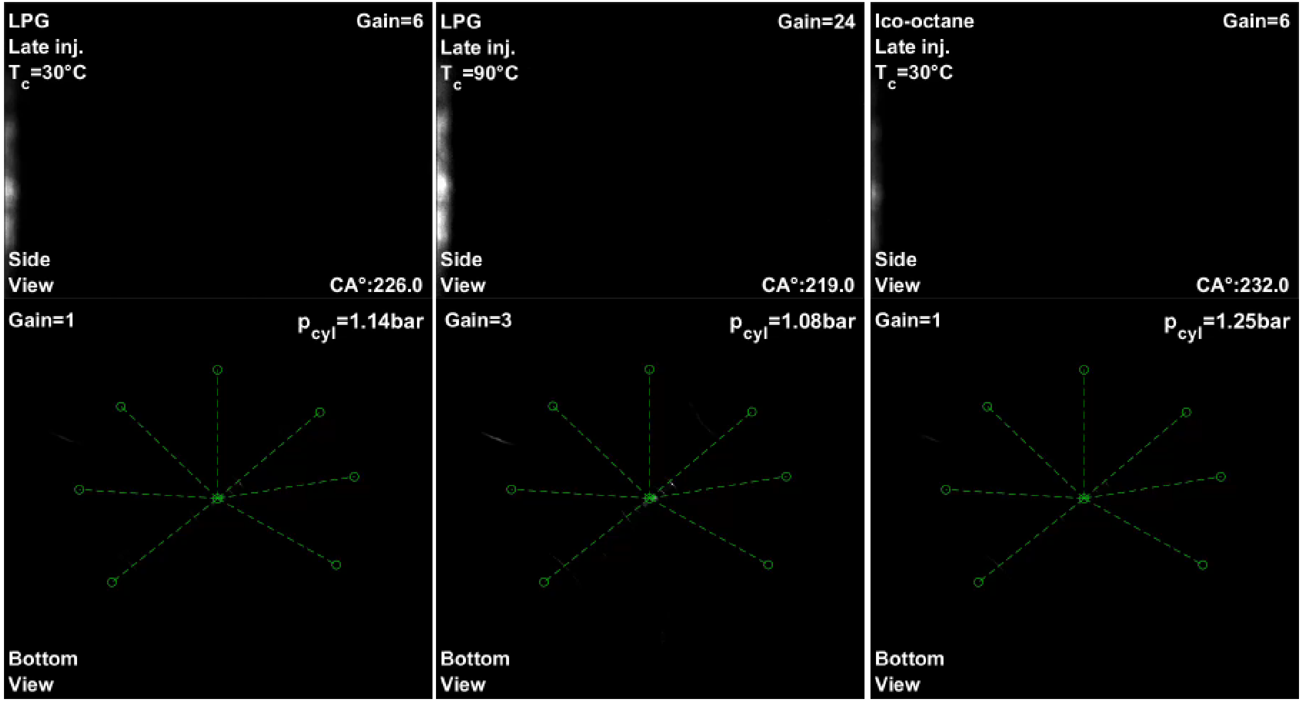
LPG spray

- At SOI the spray is fully collapsed
- During compression, as the cylinder pressure increases and individual spray-jets become distinguishable on the bottom-view
- When cylinder pressure crosses 3 bar, the spray overcomes collapse

Iso-octane (identical injector)

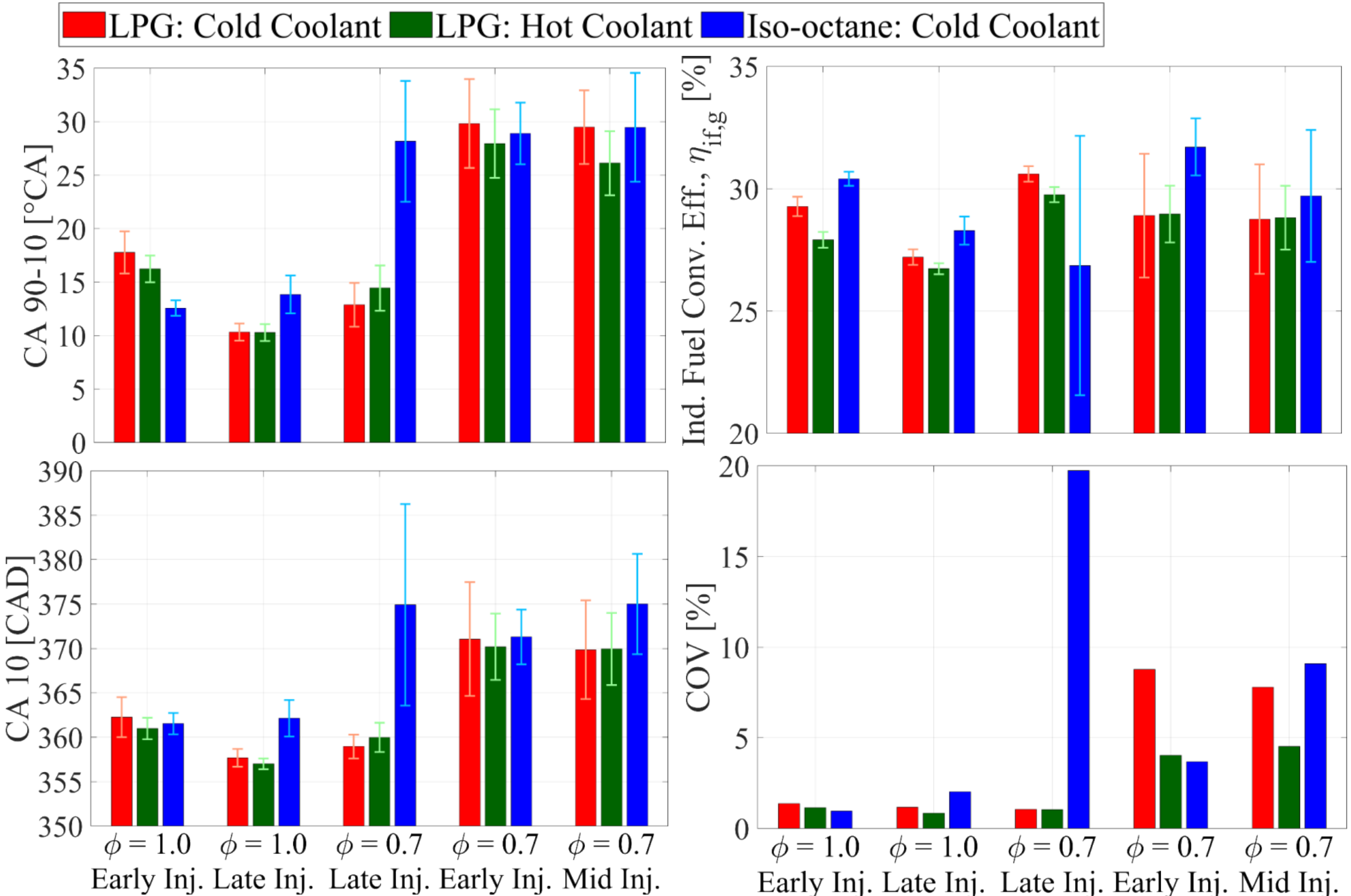
- Wider spray angle
- Individual sprays distinguishable throughout the injection duration
- The spray appears to not collapse over a range of pressure

LPG, cold (T_c=30C) | LPG, hot (T_c=90C) | Iso-octane, cold(T_c=30C)



- Top part of image: side view of the spray
- Bottom part: simultaneous bottom-view of the spray
- Green lines separate 6 nozzle zones

Stark dissimilarity in combustion duration and variability between LPG and iso-octane cases, especially with late injections



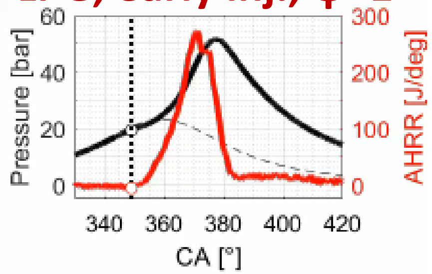
Interesting observations:

- Accelerated combustion with LPG late injection for both stoichiometric and lean conditions
- Engine-coolant temperature has no discernable influence on LPG combustion
- **Trend reversal for iso-octane** – decelerated combustion for late injections
- High tendency to **misfire with iso-octane** under lean conditions with late injection

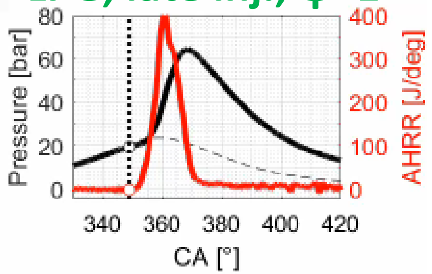
Accelerated LPG combustion and reduced variability for late injections under stoichiometric conditions

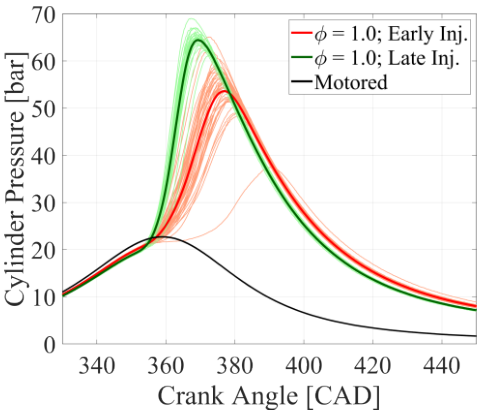
- **Late injection exhibits faster aHHR immediately after ignition**
  - Overall faster combustion
  - Reduced cyclic variability
- **Is this effect driven by mixture homogeneity or flow-field/turbulence?**
  - Steady and concentric flame evolution for early injection
  - Preferential direction for flame kernel growth under late injection, visible on both camera views
  - No obvious indication of mixture inhomogeneity

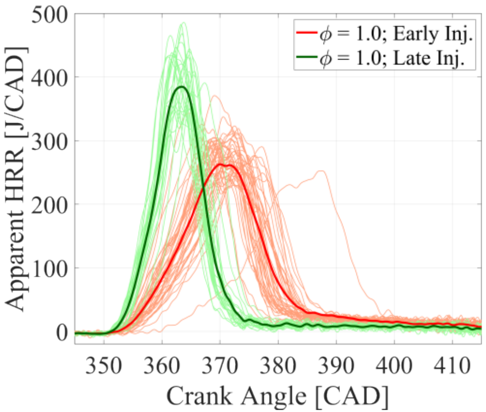
LPG, early inj., ϕ=1



LPG, late inj., ϕ=1





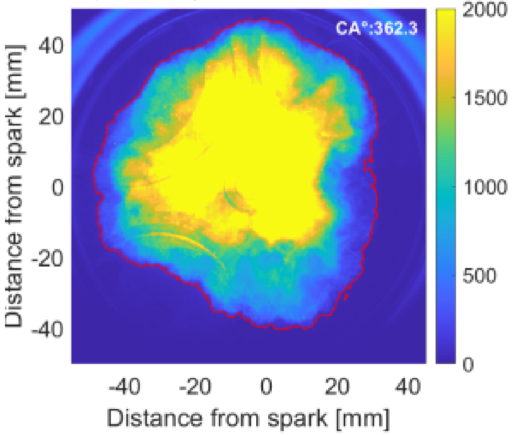


Flame contours and displacement speed can be derived from HS flame imaging using image processing

Step 1:

- In-house code with adaptive threshold approach detects the flame extent
- Wide-range of intensity
- Remove interference due to back-wall reflections

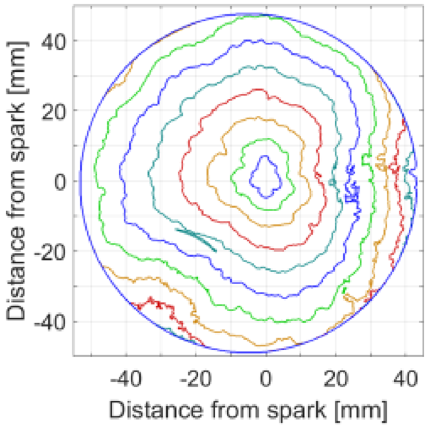
Sample image with flame contour



Step 2:

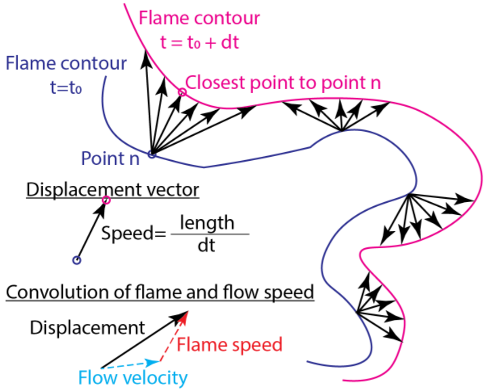
- High-speed imaging reveals temporal evolution of the contour
- 0.25CA resolution

Flame contour evolution (dt = 2CA)



Step 3:

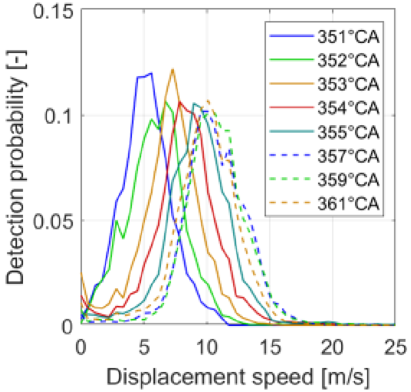
- Local flame displacement speed evaluated for each point on the contour
- Definition: smallest distance between the contour and contour from the next frame
- Convolution of flame speed and flow displacement



Step 4:

- Statistics for all acquired cycles and all points at the flame contour
- Temporal evolution of the displacement speed available

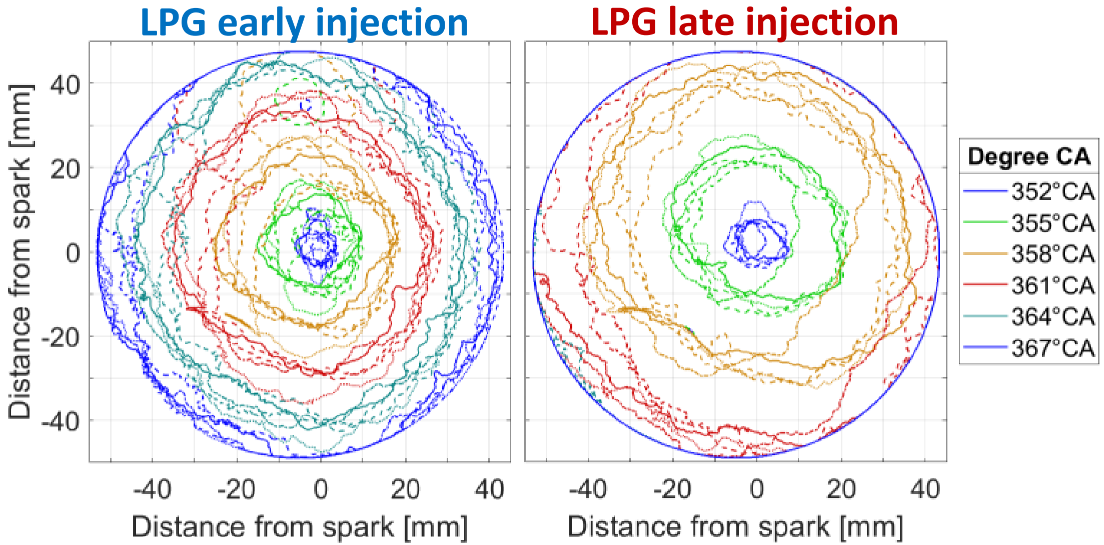
Displacement speed temporal evolution

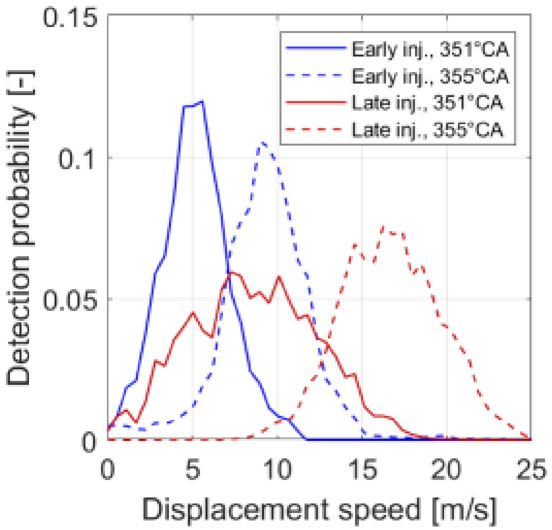


Flame is deflected for late injections and shows nearly twice higher displacement speed compared to early injection

- **Early injection: concentric flame contour evolution**
  - Small cyclic variations in flame contour
- **Late injection: Preferential direction of flame contour evolution**
  - Fairly repeatable flame evolution in line with low CoV
  - Much faster flame propagation as expected
  - Combined tumble-like motion and mixing most likely causes the deflection of flame contours

- **Slow early flame displacement, stabilizes at a steady value after a few CAD**
- **Broader distribution with late injection indicates the effect of flow-field and turbulence**
  - Flame deflection caused by the flow will result in wider distribution of detected displacement speed
  - Turbulence is an important factor: dissimilar displacement speeds between early and late injections

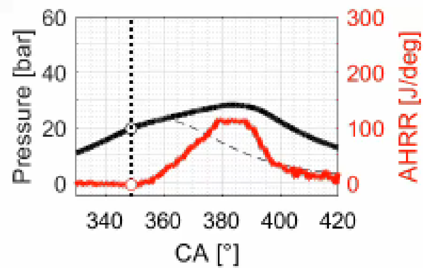


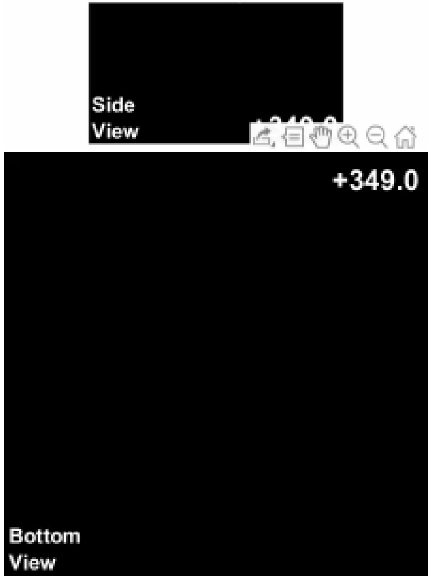


Late-injection lean LPG case achieves fast and stable combustion contrary to the early-injection lean cases

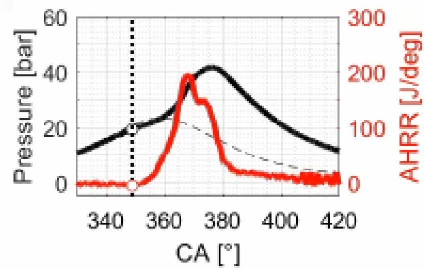
- **Lean conditions amplify the injection timing effects observed under stoichiometric conditions**
  - Late injection shows rapid onset of combustion characterized by short combustion duration
  - Early and intermediate injections exhibit a slow and highly variable combustion evolution
- **Late injection likely generates inhomogeneous mixtures**
  - Non-spherical flame-front, large structures visible
  - Large variations in flame luminosity indicate inhomogeneous mixture (potentially soot?)

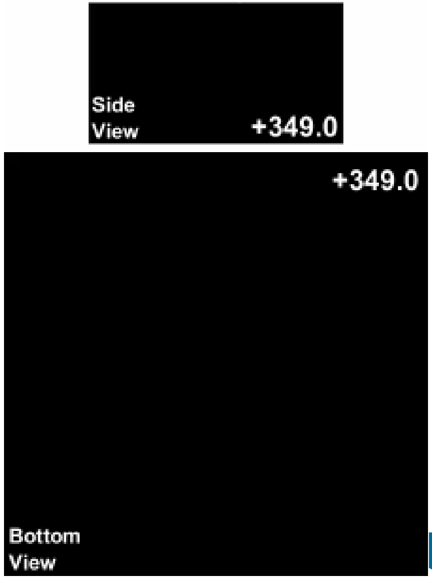
LPG, early inj., ϕ=0.7

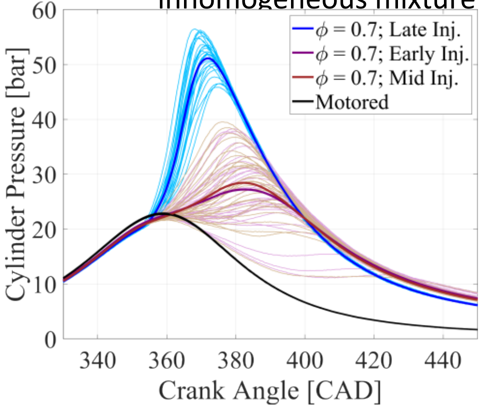


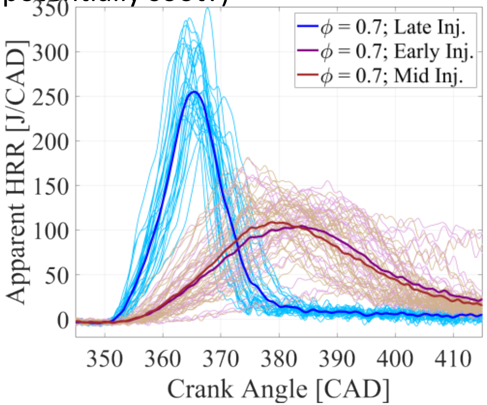


LPG, late inj., ϕ=0.7





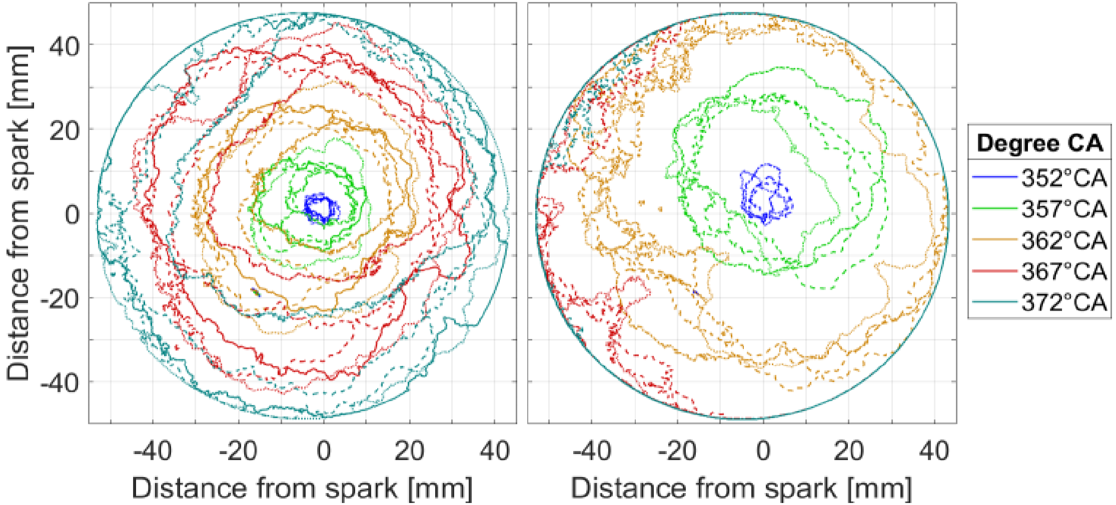


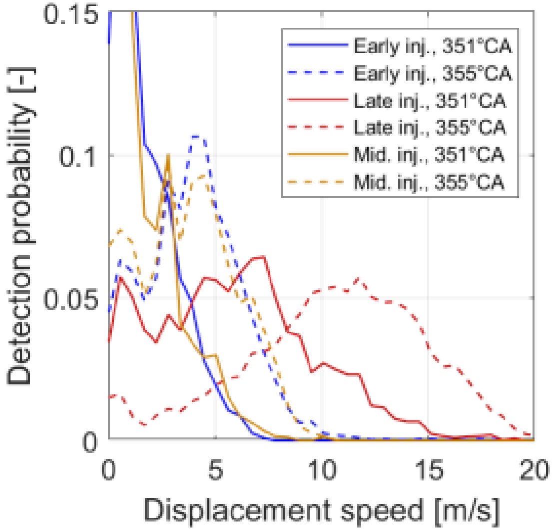


High fluctuations of contour evolution and displacement speed for lean combustion except with late injection

- Early injection (ϕ=0.7): Concentric flame contour evolution
  - Selected cycles have similar value of CA but the flame contour evolution is less repeatable
  - Fairly concentric flame evolution
- Late injection: Repeatable deflection of flame
  - Very fast flame propagation with repeatable deflection of flame contours
- Late injection (ϕ=0.7) shows only about 20% reduced displacement speeds compared to stoichiometric operation
  - Larger scatter at ignition, broader distribution of displacement speed potentially indicates mixing inhomogeneity
- Early/mid. injections exhibit low displacement speed
  - High probability for detection of low values, again probably due to mixing

LPG early injection (ϕ=0.7) LPG late injection (ϕ=0.7)

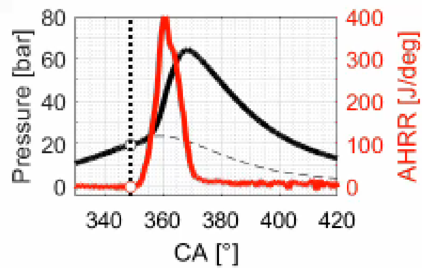




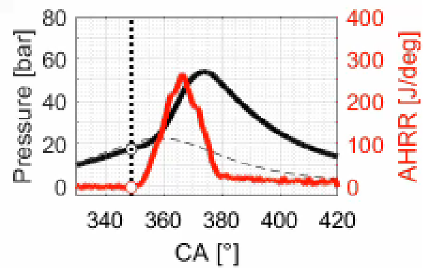
Slower combustion and higher variability of late injection octane case relative to LPG (ϕ=1)

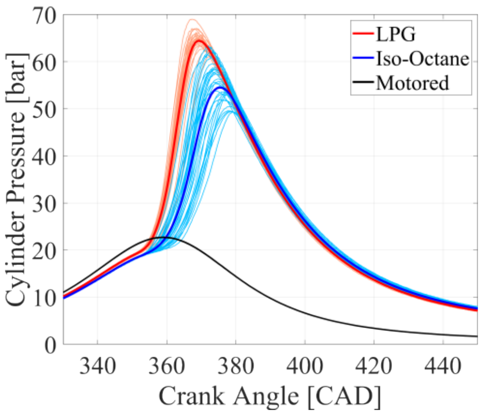
- **Spray collapse and liquid-length are the only apparent differences between LPG/iso-octane**
  - Significant changes in flame speed, combustion duration and cyclic variability
- **Is this effect driven by mixture homogeneity or flow-field/turbulence?**
  - Constant time since the end of injection, but different spray pattern might change the flow field
  - Similar evolution of flame contour, mostly changes in the propagation speed

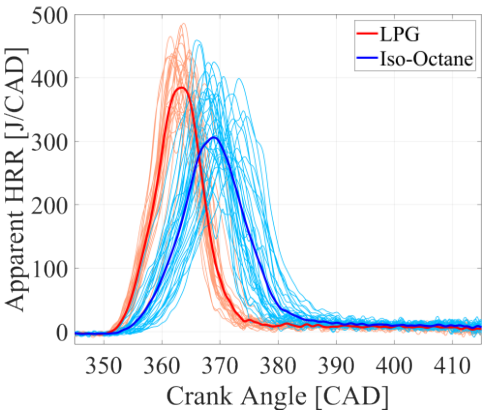
LPG, late inj., ϕ=1



Octane, late inj., ϕ=1



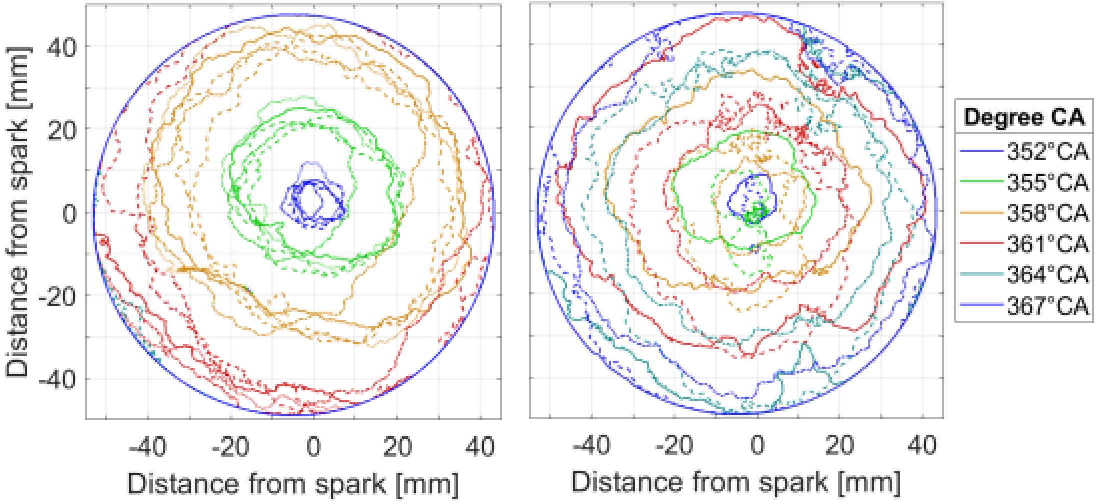


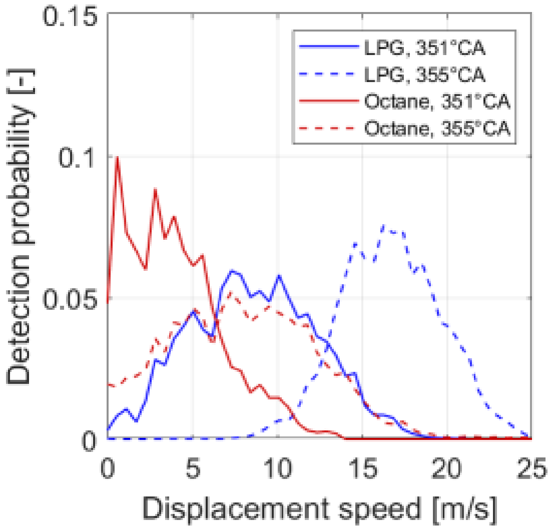


Non-repeatable flame evolution and wide distribution of displacement speed indicate inhomogeneous mixture for iso-octane

- **Octane late-injection generates varying flame contour evolution at same value of CA10**
  - No preferential direction detectable
  - In general, combustion is slower despite a few fast cycles detected at random
  - Large differences in the size of initial kernel at 352CA (blue contour)
- **Octane (ϕ=1) shows about 20% slower displacement speed than LPG (ϕ=1) with same late injection timing**
  - Comparable displacement speed to lean LPG (ϕ=0.7) case
- **Large probability of near-zero displacement speeds during initial flame kernel growth**
  - Strong indication of mixture inhomogeneity, possibility of ultra-lean mixtures near the spark location
  - Even more pronounced under lean conditions (not shown)

LPG late injection (ϕ=1) **Octane late injection (ϕ=1)**





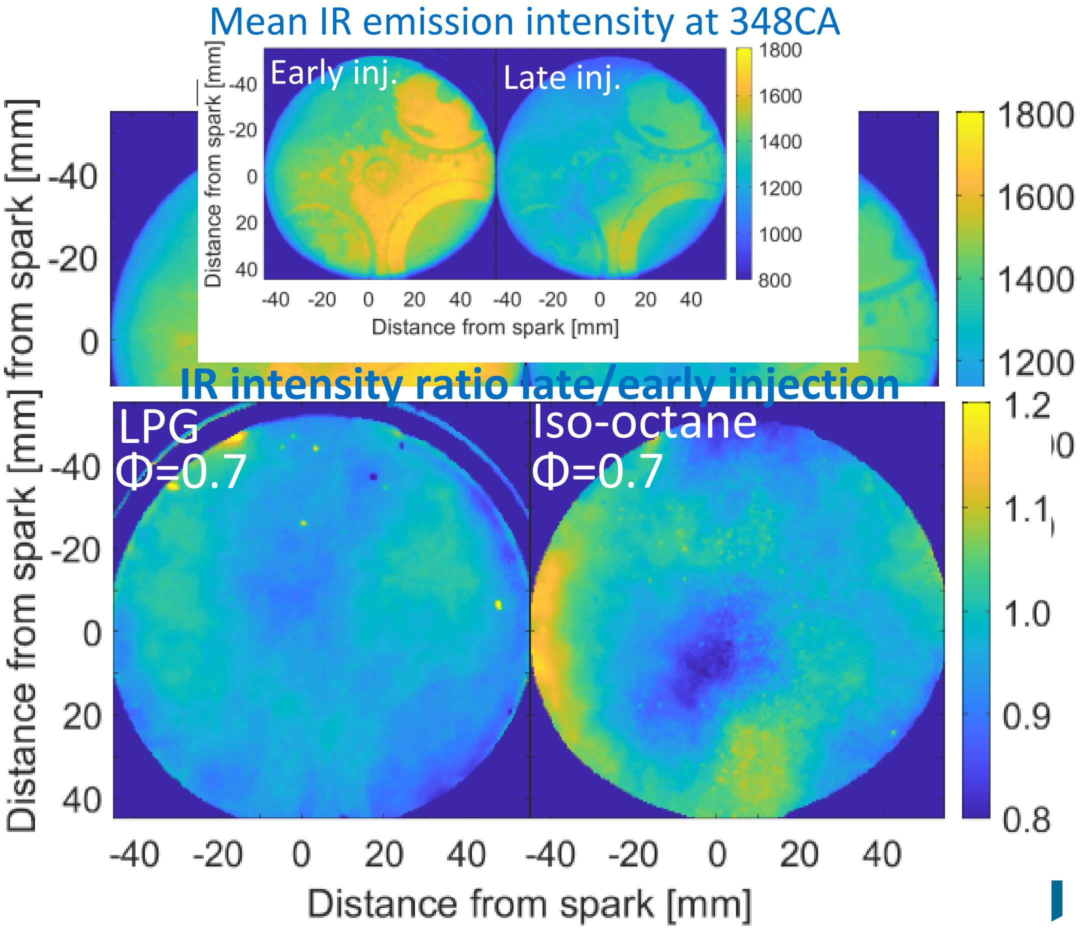
IR imaging indicates consistently reduced fuel concentration near the spark-location for late iso-octane injection

Qualitative insight into mixture distribution using ensemble-averaged IR images at 348 CAD

- Ensemble averaged IR signal just before spark timing does not show any noticeable differences between early and late injection timings.
- Observed differences in intensity is primarily due to evaporation cooling caused by late injections.

Normalize the spatial IR emission intensity of late injection by the distribution from early injection

- **Assumption:** early injections result in a fairly homogeneous mixture → the ratio between IR distributions shows coherent differences in IR intensity.
- **LPG:** No significant differences observable
- **Iso-octane late injection**: coherent regions of reduced IR intensity near the spark location.
- Most likely indicates distribution of leaner mixtures in the vicinity of the spark, leading to increased misfires



Conclusions and remaining barriers

Summary and conclusions

- **LPG DI fuel injection and laser-spark ignition** system realized in a heavy-duty, single-cylinder optical diesel engine under lean and stoichiometric engine operation.
- **Strong spray collapse induced by LPG**: Not avoidable by asymmetric-nozzle injector design.
- **Early injection timing can create a fairly homogeneous** mixture for both LPG and iso-octane – repeatable flame evolution for both fuels under hot or cold coolant temperatures
- **Late injection timing results in mixture inhomogeneity** and non-isotropic (spatial variations) turbulence distribution
  - LPG combustion benefits from more favorable mixture distribution and flow properties induced by collapsed spray
  - Detrimental for iso-octane, likely distribution of lean mixture near the spark

Remaining barriers, future direction

- **Inadequate science base and hardware for SI of LPG in MD/HD engines**
- Low efficiency and knock limitations, particularly with iso-octane.
- Adoption of LPG as SI fuel in MD/HD engines might face **challenges especially in terms of spray targeting** for stratified operation – compatibility with gasoline DI engines is questionable
- **Preparation of a homogeneous mixture using LPG appears to be relatively straightforward**
  - Potential for combinations with advanced ignition systems and high-EGR or lean operation

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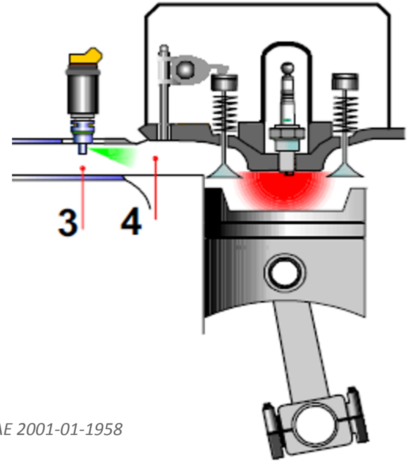
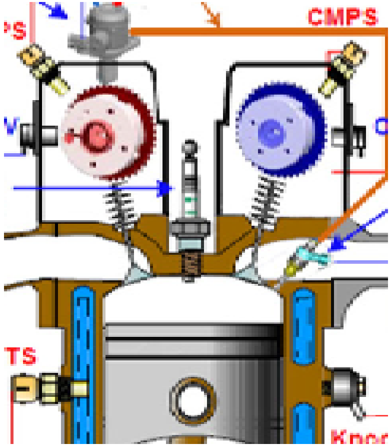
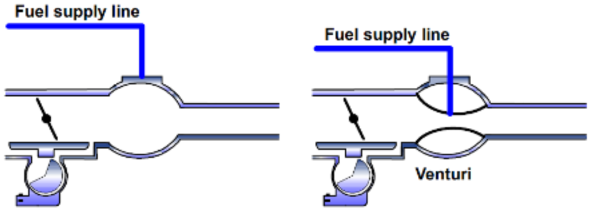
Thank you for your attention!

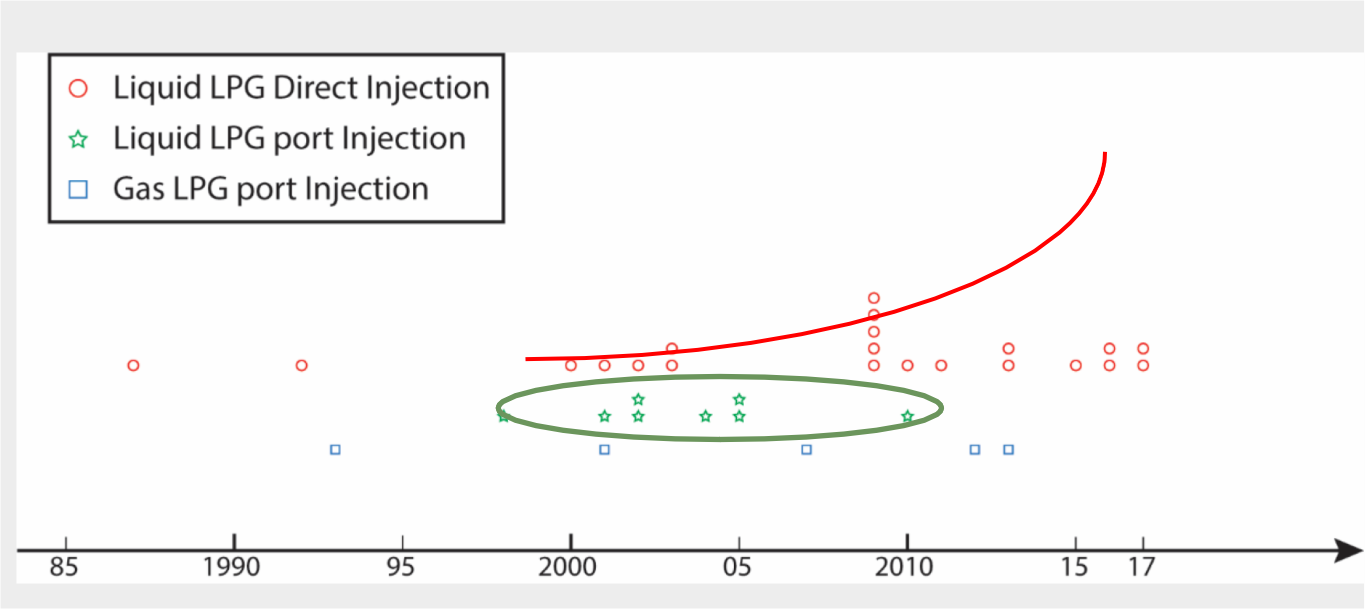
Contact: asrna@sandia.gov (Aleš Srna)

Three types of propane fuel delivery in the literature

	Port Fuel Injection	Direct Injection
Liquid LPG	 SAE 2001-01-1958	 *Fuel processing tec. Juwon Kim. etc*
Gaseous LPG	 *SAE 2001-01-1958*	

LPG DI research is of more interest than LPG PFI in recent years due to its higher power density

year	title	fuel supply type	institutions
1993	932641	g p SI	
2010	2010-01-1461	DISI LPG/Gasoline	Korea
2015	2015-01-1947	DISI LPG knock	Australia group
2000	Seoul 2000 FISITA Goto.	LPG SI and CI HD	Japan
2009	2009-01-1881	LPG DISI	Australia group
2016	2016-01-2255	LPG DISI	
2010	2010-01-0336	liquid LPG port injection DME dual fuel HCCI	korea
1987	872095	liquid propane DI CI	
2016	2016-01-0842	Propane GDI SI CVC	australia group

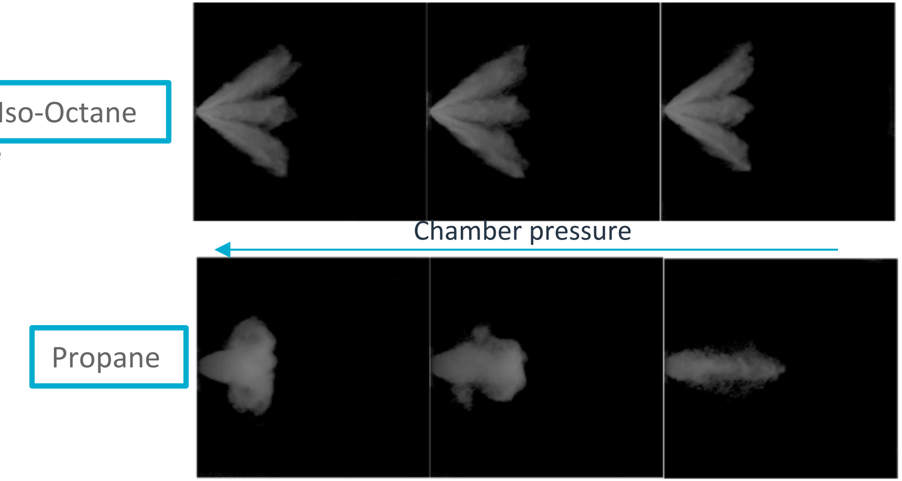


Previous work in constant-volume chambers show greater spray collapse for propane compared to iso-octane

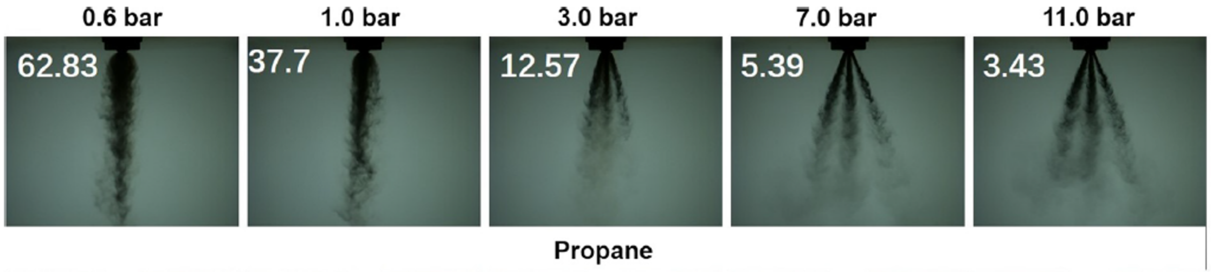
<u>Previous optical work in a constant-volume chamber:</u>

- Spray collapse observed with a multi-hole injector
- Compared to iso-octane at the same condition, the propane liquid spray collapses

** SAE Lacey, J., Poursadegh, F., Brear, M., Petersen, P. et al., "Optical Characterization of Propane at Representative Spark Ignition, Gasoline Direct Injection Conditions," SAE Technical Paper 2016-01-0842*



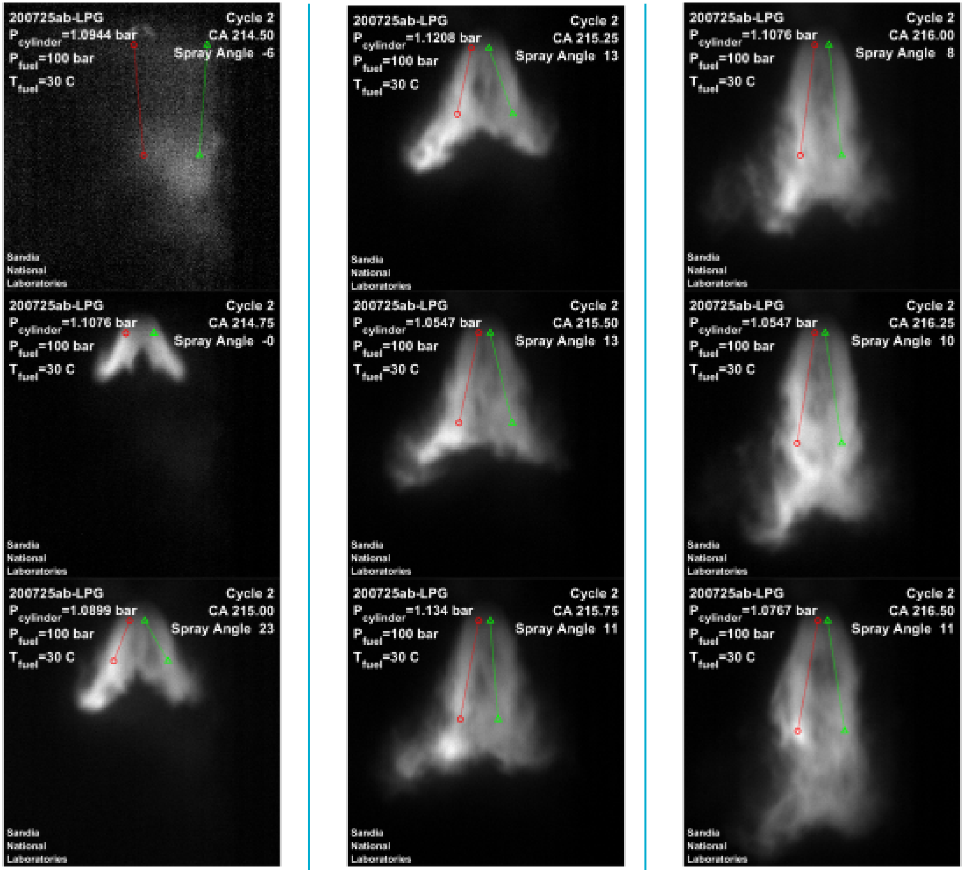
- Below 3 bar ambient pressure, the multi-hole flash-boiling sprays collapse; above 3 bar ambient pressure, the sprays do not collapse with each jet penetrating nearly along its original trajectory



Li, Yanfei, Hengjie Guo, Zhifu Zhou, Zhou Zhang, Xiao Ma, and Longfei Chen. "Spray morphology transformation of propane, n-hexane and iso-octane under flash-boiling conditions." Fuel 236 (2019): 677-685.

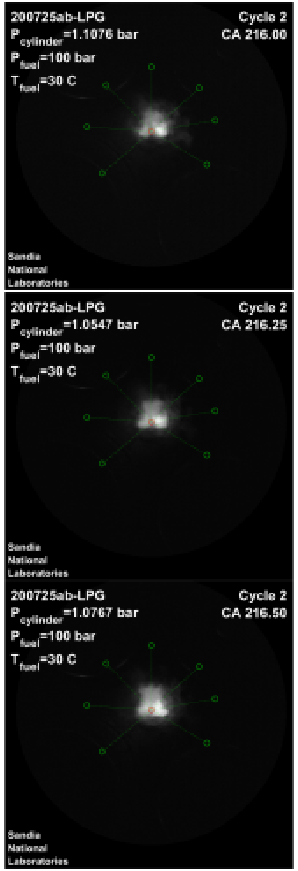
LPG spray collapse at 1 bar, 60C intake T and 30C fuel T

ECN G@EOI side view

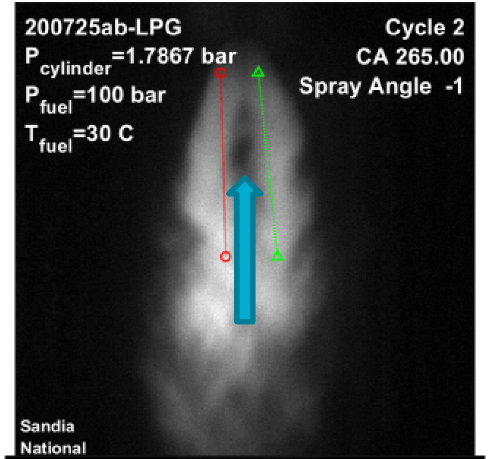


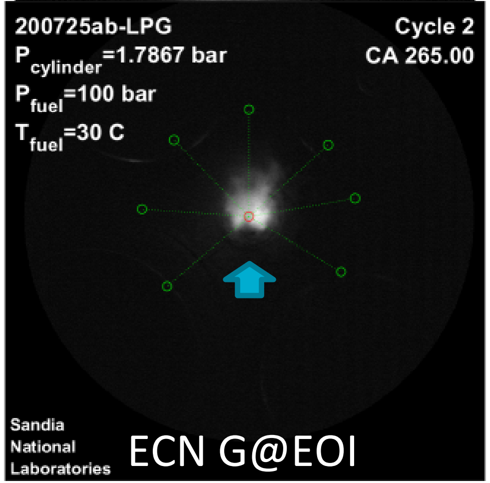
- The included angle of the spray pattern is computed between the red and green lines indicating the apparent spray axes
- The initial full included angle is greater than 20˚ after only 2 ˚CA, it decreases to less than 10˚ as the propane sprays collapse
- The bottom-view show that once spray collapse, the individual spray merges

Bottom view

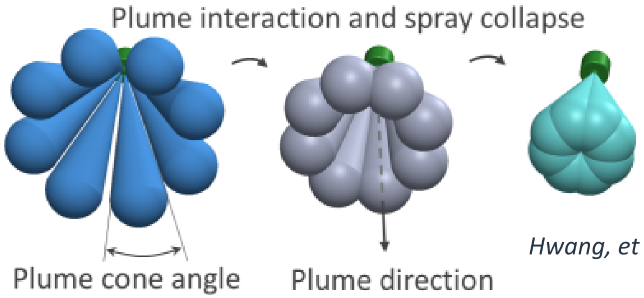


Spray collapse occurs even with this asymmetric spray pattern having an opening in one quadrant of the spray envelope





- Symmetric spray patterns are prone to collapse
  - If the (spray plume cone) expansion is significant enough, adjacent spray plumes are able to interfere with one another, and in the most extreme case, this plume-to-plume interaction results in severe spray collapse[1].



Hwang, et al., 2019 Aug AEC talk

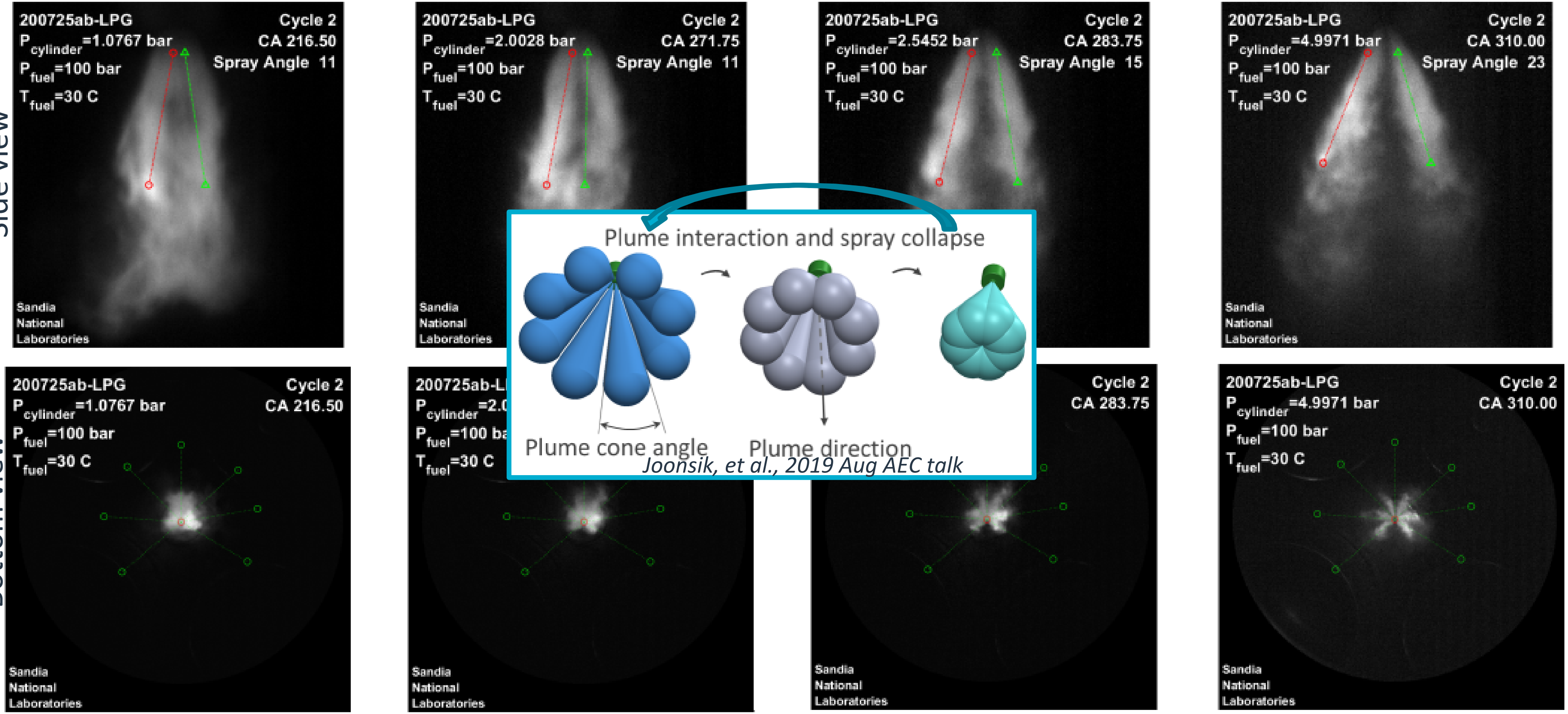
- Entrainment/recirculation is less confined with an asymmetric spray pattern, yet propane still collapses.

[1]. *Lacey, J., et al. "Generalizing the behavior of flash-boiling, plume interaction and spray collapse for multi-hole, direct injection." Fuel 200 (2017): 345-356.*

The propane spray evolves during the early compression stroke: it collapses during 1 bar intake, then opens when cyl. Press. > ~2.5 bar

ECN G@EOI Side view

ECN G@EOI Bottom view



1 bar, collapse

2 bar, collapse

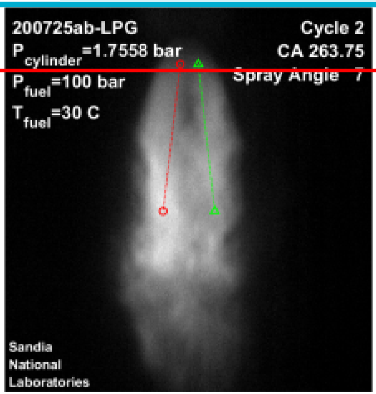
2.5 bar, collapse -> open

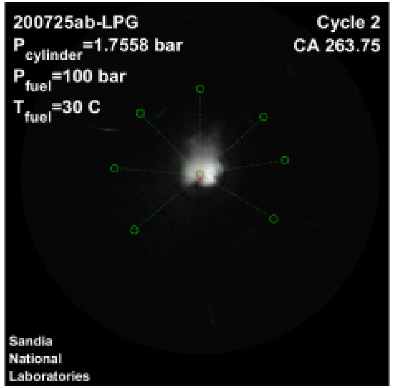
ECN G, 310 CAD non-collapse

Although a collapsed spray can open up, the threshold cyl. P is higher than for a later injection starting at a higher initial cyl. P

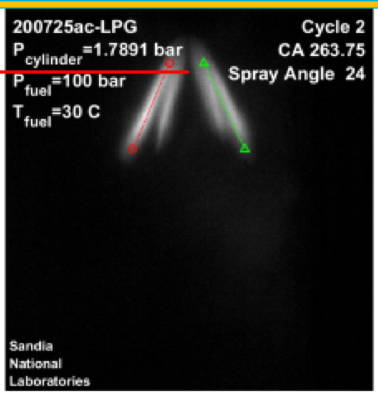
Side view

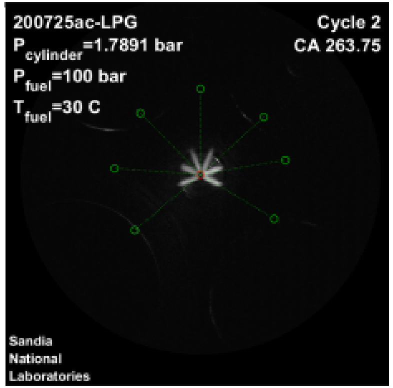
Bottom view



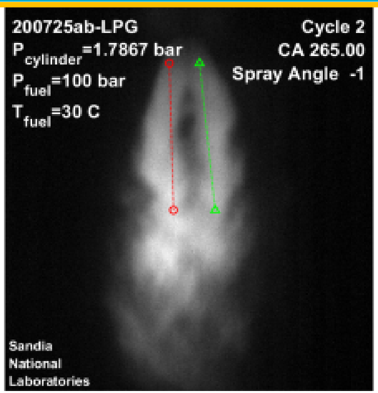


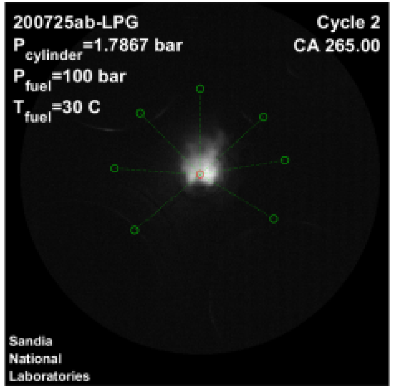
ECN G@EOI
SSE 214, collapse



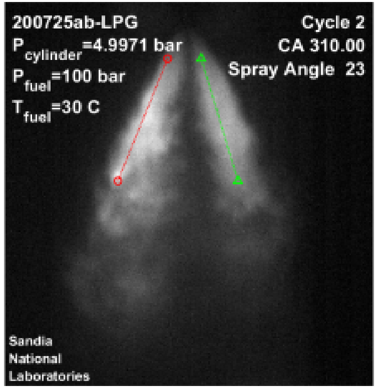


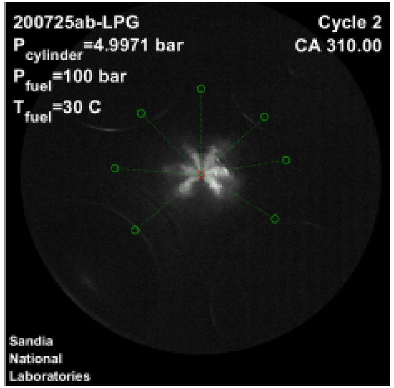
ECN G@EOI-Late
SSE 263, Non-collapse





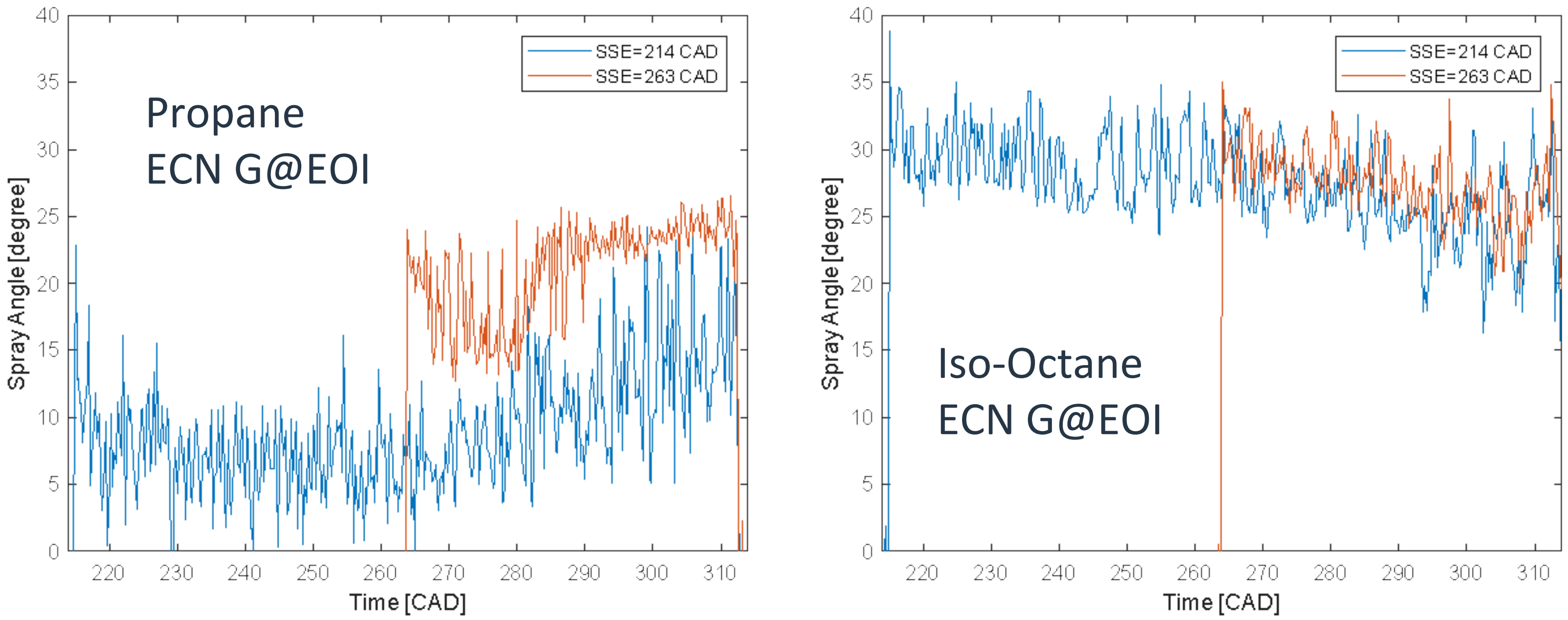
ECN G@EOI
SSE 214, collapse





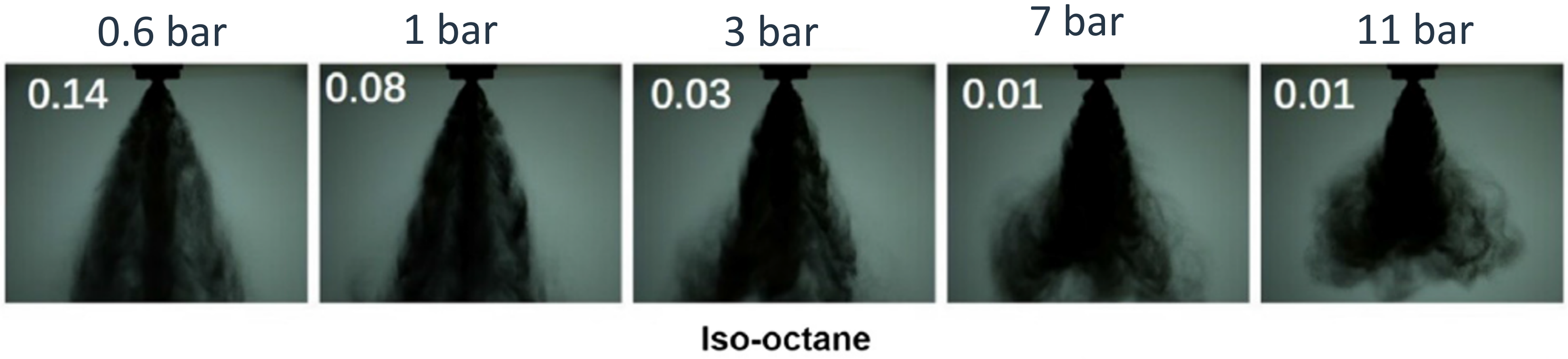
ECN G, 310 CAD
non-collapse

Included angle for propane is decreased by spray collapse during intake stroke, while non-collapsing iso-octane is not affected



Sprays that collapse during the early part of injection tend to stay collapsed during compression, even if a later injection at the same pressure would not collapse. Non-collapsing sprays are identical to later injection.

Condensation-induced collapse could be a potential explanation for the iso-octane spray collapses at 2 bar



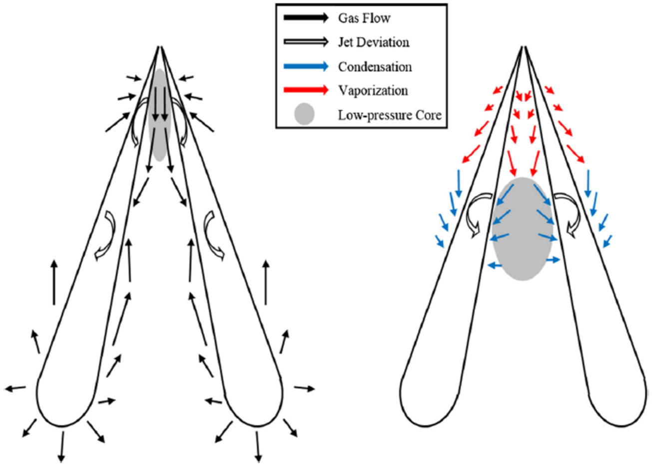


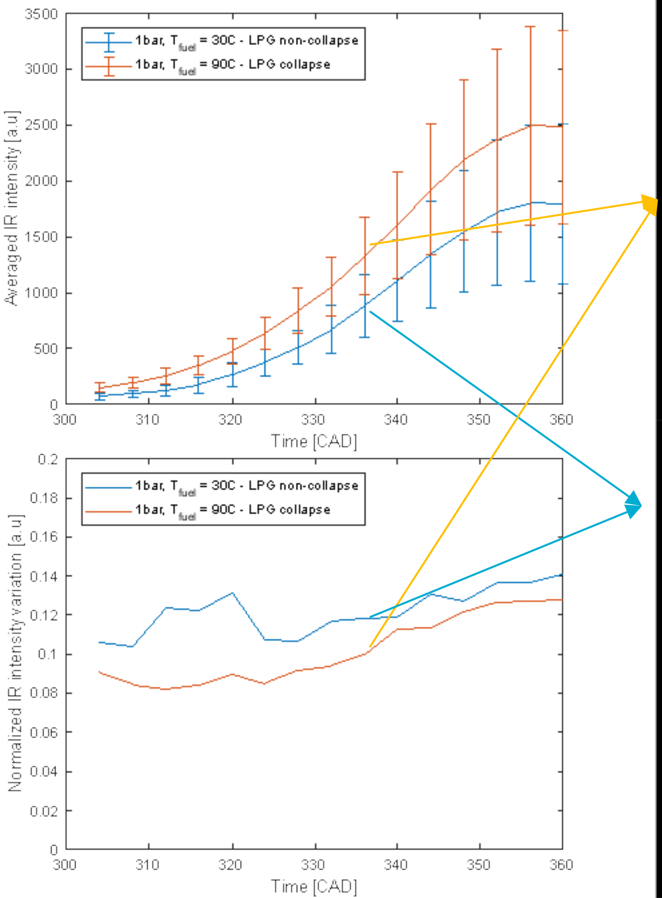
Fig. 10. Mechanisms of the jet-induced spray collapse (left) and the condensation-induced spray collapse (right).

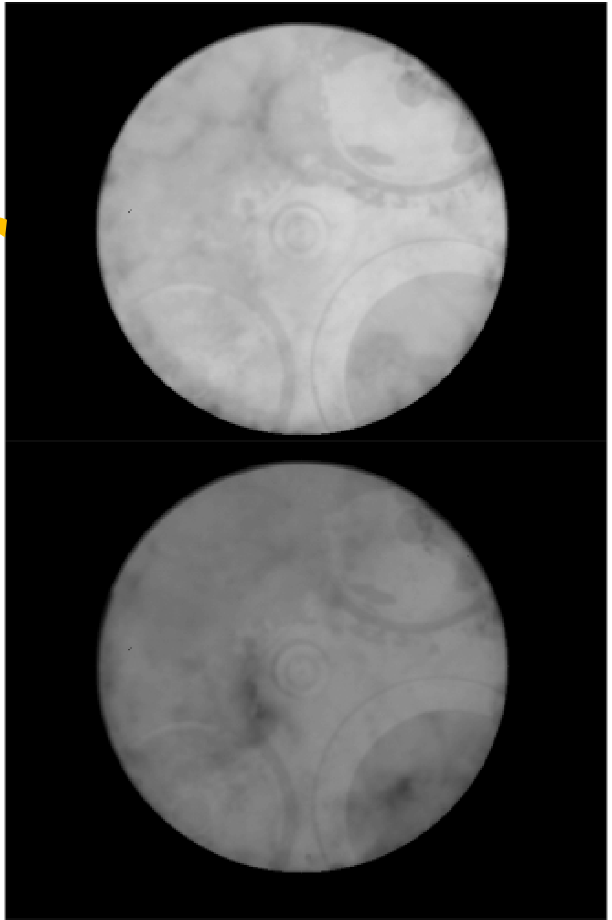
The occurrence of condensation would greatly reduce the partial pressure of vapor inside the spray and produce a local low pressure zone, leading to the collapse.

Guo, Hengjie, Haichun Ding, Yanfei Li, Xiao Ma, Zhi Wang, Hongming Xu, and Jianxin Wang. "Comparison of spray collapses at elevated ambient pressure and flash boiling conditions using multi-hole gasoline direct injector." Fuel 199 (2017): 125-134.

IR images of LPG show some degree of less homogeneity for collapse condition than non-collapse at 336 CAD for late injection

- IR emission is from the C-H bend and its intensity reflects combination of temperature and concentration.
- Try to see how does spray collapse affect mixing on IR.
- Both cases have same intake condition, LPG mass injected and EOI. But 90C fuel T has the spray collapse, the 30C spray collapse initially and open up later.
- The averaged IR image intensity shows 90C is higher than 30C due to higher temperature
- The error bar in the plot is one standard deviation of pixel intensity in the image. The 90C has larger error bar, however it is biased by the absolut intensity.
- The lower plot has all images normalized between 0 and 1, then compute the standard deviation. It shows that 30C deviation is larger which indicated less homogeneity.



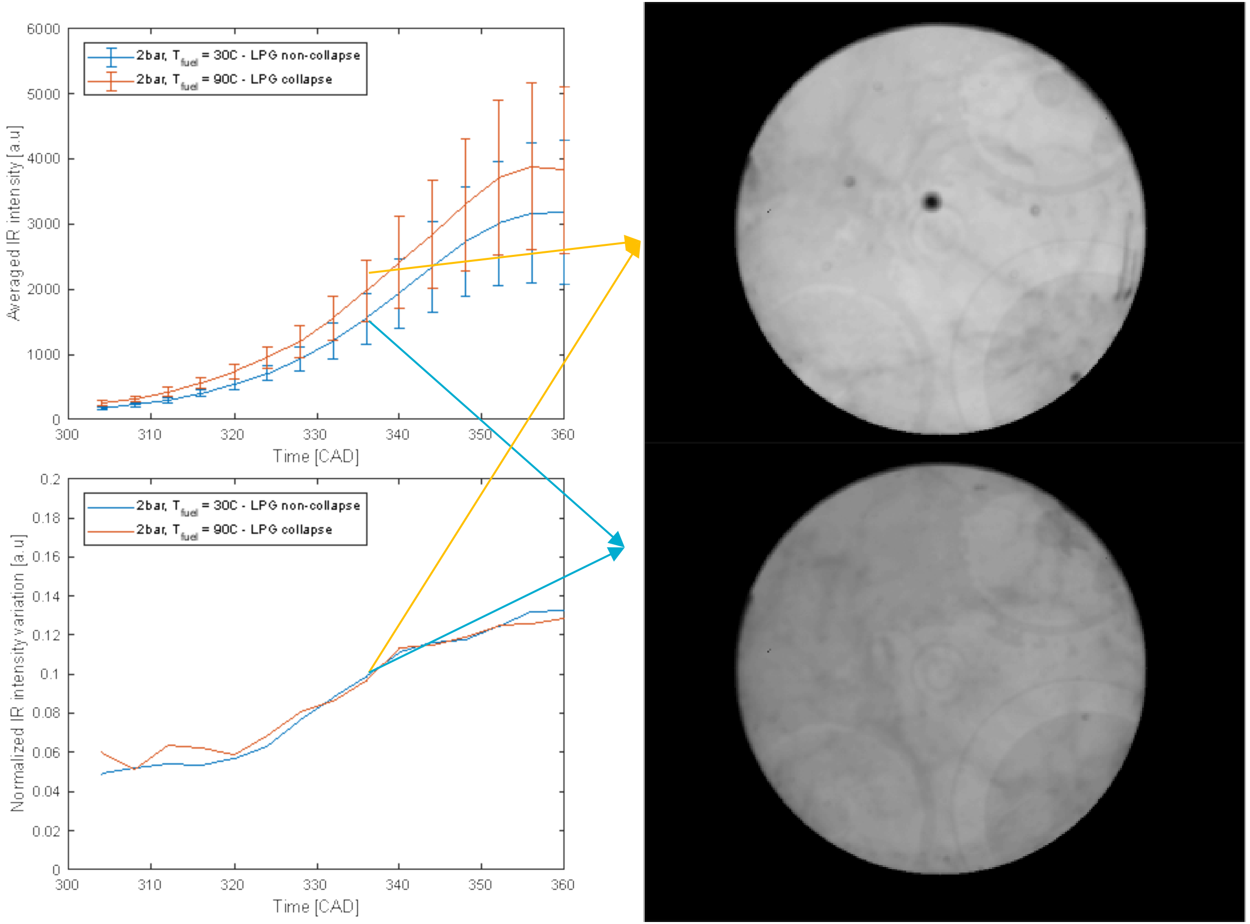


ECN G-Late
SSE=263
90C fuel T
Collapse

ECN G-Late
SSE=246
30C fuel T
Non-collapse

IR images of LPG show identical homogeneity for collapse condition and non-collapse at 336 CAD for early injection

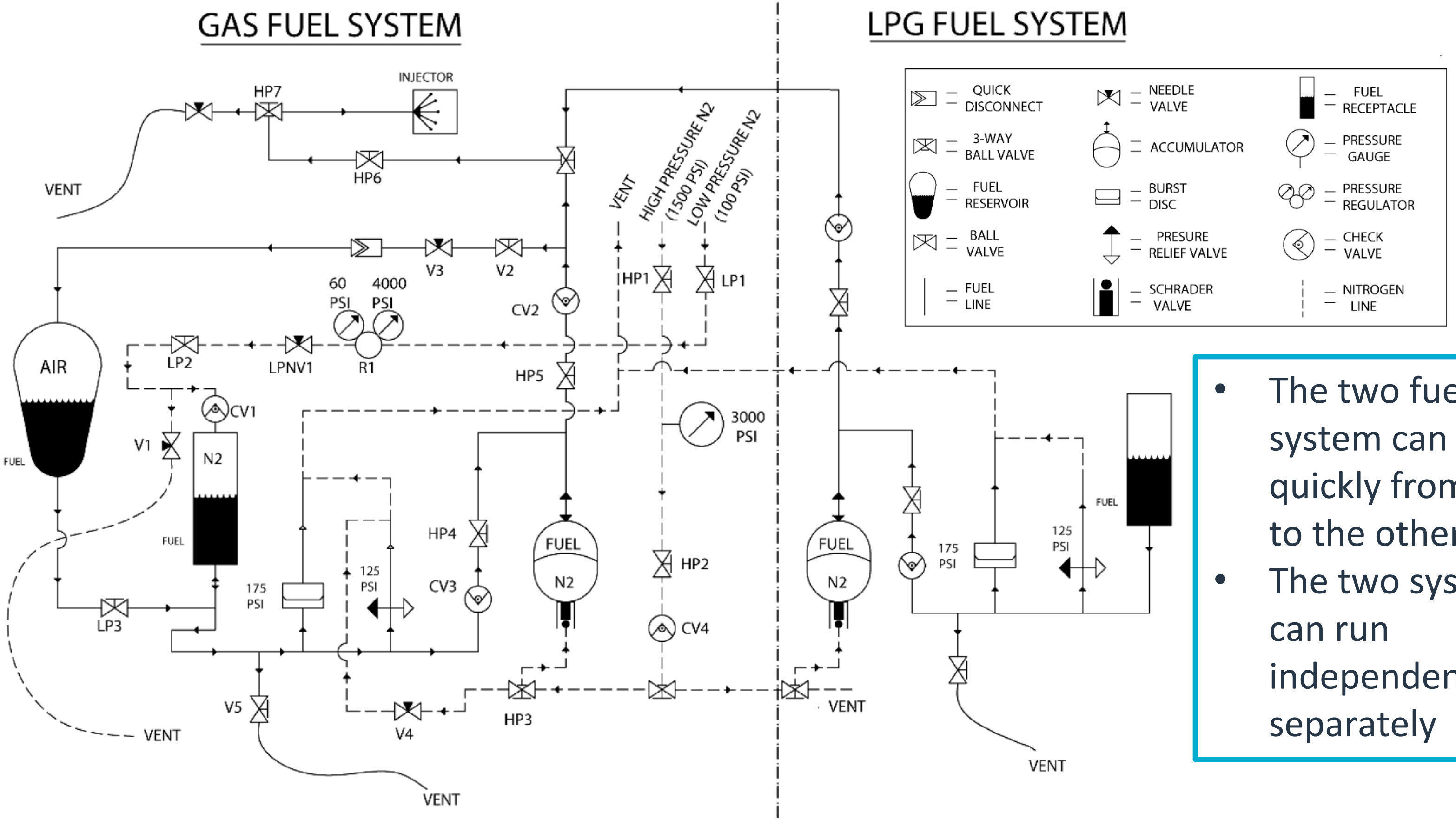
- Both cases have same intake condition at 2 bar, LPG mass injected and EOI. But 90C fuel T has the spray collapse, the 30C spray collapse initially and open up later.
- The averaged IR image intensity shows 90C is higher than 30C due to higher temperature
- The lower plot has all images normalized between 0 and 1, then compute the standard deviation. It shows that 30C deviation is larger which indicated less homogeneity.
- This suggests that on an early injection case with enough time for mixing the spray collapse doesn't affect mixture homogeneity.



High pressur
SSE=60
90C fuel T
Collapse

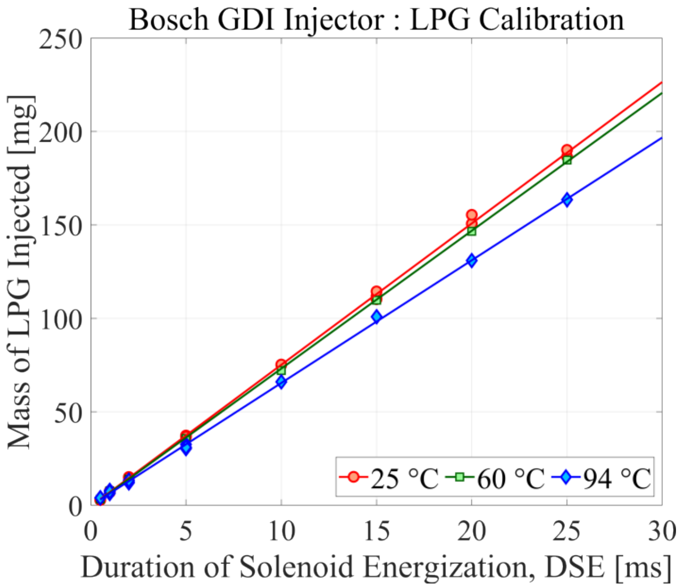
High pressur
SSE=60
30C fuel T
Non-collapse

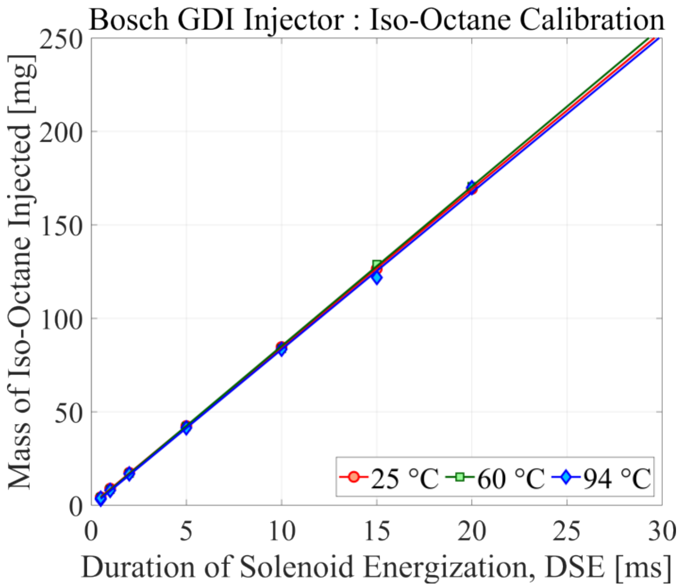
Parallel propane and iso-octane fuel supply system allows quick switching between the two fuels



- The two fuel system can switch quickly from one to the other
- The two systems can run independently and separately

The propane injection rate reduces with higher fuel temperature due to the higher superheated degree of flash boiling





- The fuel temperature could significant affect the mass flow rate from this injector for propane.
  - This is mainly due to that the saturation pressure for propane is higher than 1bar and propane is in gas phase at room pressure. The higher fuel temperature is causing more severe flash boiling and restricting the flow in the orifice.
  - However, for iso-octane is in liquid phase in room pressure and the flow rate is almost not affected by flash boiling(fuel temperature).
- This could be an issue for propane DI engine calibration if the injector temperature is not controlled.

Engine liner window broke on the fired engine test

- In the optical engine configuration, 532 nm, 100 mJ/pulse laser was used generating a plasma spark for fired cycles.
- The liner window for the laser access broke during the experiment on Aug 2nd.
- It wasn't clear whether the window crack is due to laser drill on the window.
- We do get the laser spark and have a few fired test runs with octane.
- We will replace the liner window and continue to fire the engine with LPG DI.