

# Abstract

SAND2020-12035PE

Liquid Petroleum Gas (LPG) is an alternative fuel for transportation engines and is already in use for many fleet vehicles. However, most current LPG-fueled engines use port-fuel injection which has lower power density than a gasoline engine of equivalent displacement due to the lower molecular weight and higher volatility of LPG components yielding a much larger volume of gaseous fuel that displaces more air in the intake charge. LPG direct-injection during the closed-valve portion of the cycle can avoid displacement of intake air and achieve comparable power density to gasoline engines with equivalent displaced volume. Under some engine operating conditions, direct-injection sprays can collapse and lead to sub-optimal fuel-air mixing, wall-wetting, incomplete combustion, and increased pollutant emissions. Due to its thermophysical properties, direct-injection LPG can be even more prone to spray collapse than gasoline sprays, though the impacts on mixing for high-volatility LPG is not as well understood as for gasoline. In this work we focus on direct-injection experiments using propane, and surrogate for LPG, in a heavy-duty optical engine to study propane spray collapse and its consequences on fuel-air mixing. A quick-switching parallel propane and iso-octane fuel system is demonstrated. The fuel temperature and ambient pressure are swept. Unlike constant-volume chamber spray experiments, the pressure and temperature in the engine are dynamically varying during the compression and expansion strokes. With an intake pressure of 1 bar, the propane spray collapses initially, but as the pressure increases during the compression stroke, the collapsing spray gradually opens up at 2.5 bar and recovers to a non-collapse condition by the end of injection when the cylinder pressure is 5 bar, potentially due to a weaker flash-boiling effect at higher pressures. When the propane spray initially collapses, it tends to stay collapsed through transient conditions at which a new starting injection would not collapse. Also, for some higher cylinder-pressure conditions, iso-octane sprays collapse at least partially while propane sprays do not. Condensation-induced collapse might be at play for collapsing iso-octane sprays at these conditions. Imaging of infrared emission from compression-heated fuel does not reveal any large differences in signal distribution between collapsing and non-collapsing sprays at the spark timing for the very long injections investigate here, and in some cases a collapsed spray may yield a more homogeneous signal distribution.



## Updates on Propane Direct-Injection Experiments in a Heavy-Duty Optical Engine

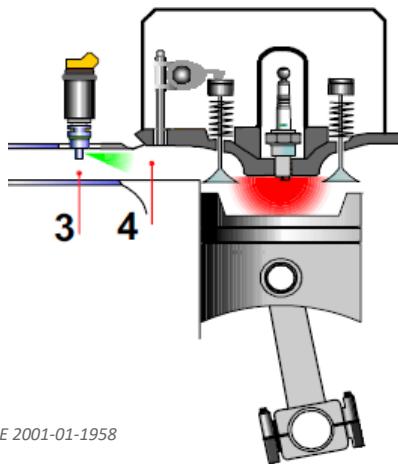
Zheming Li<sup>1</sup>, Rajavasanth Rajasegar<sup>1</sup>, Yoichi Niki<sup>2</sup> and Mark P.B. Musculus(P.I)<sup>1</sup>

*<sup>1</sup>, Combustion Research Facility, Sandia National Laboratories*

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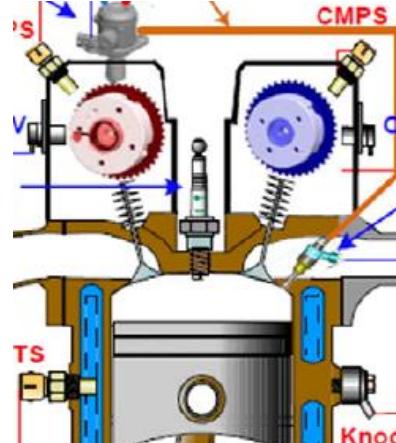
DOE program managers: Gurpreet Singh, Michael Weismiller

## Port Fuel Injection



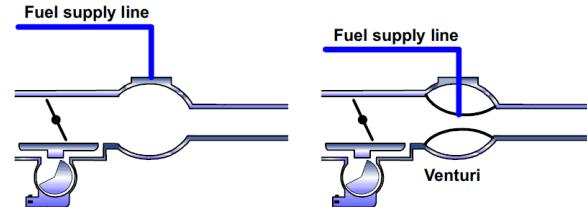
SAE 2001-01-1958

## Direct Injection



Fuel processing tec. Juwon Kim. etc

## Gaseous LPG

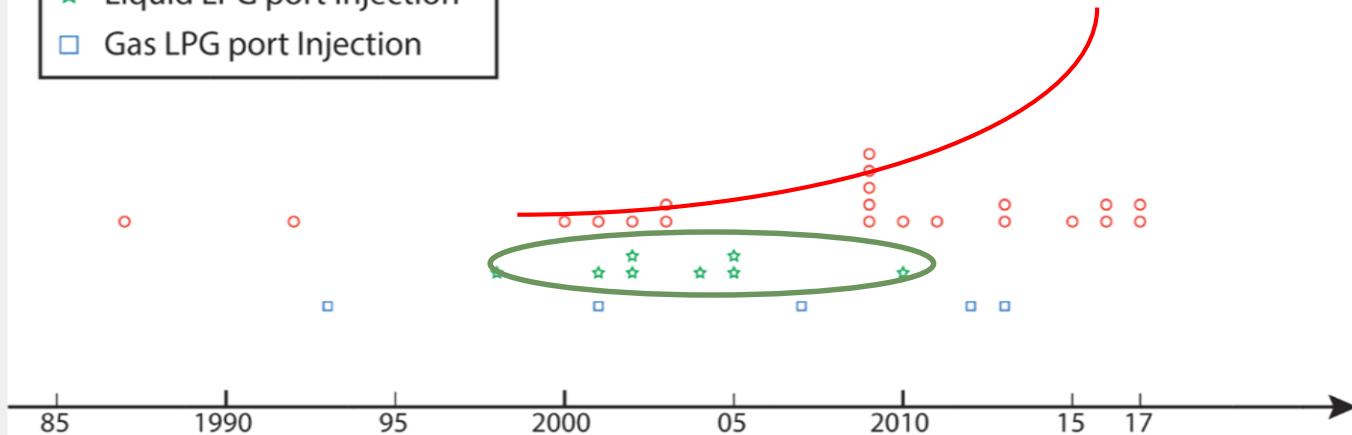


SAE 2001-01-1958

# 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                         | 932641g 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 2016-01-0812            | Propane GDI SI CVCI                          | australia group  |              |

- Liquid LPG Direct Injection
- ★ Liquid LPG port Injection
- Gas LPG port Injection



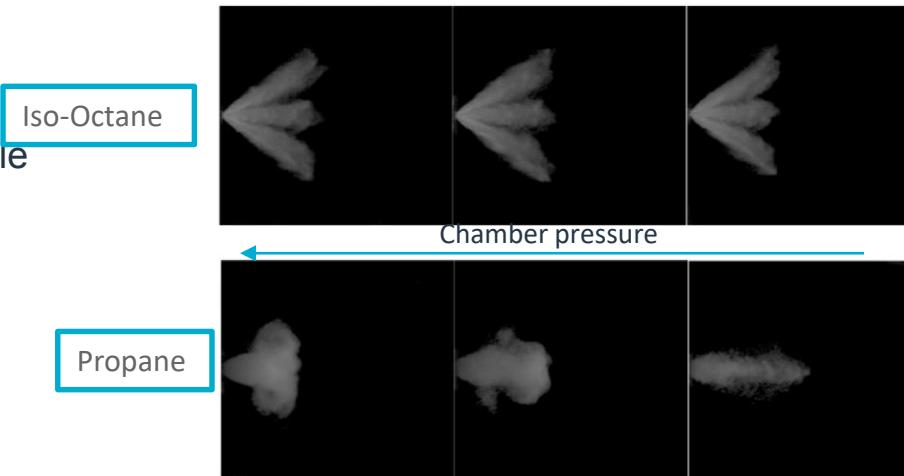
# Previous work in constant-volume chambers show greater spray collapse for propane compared to iso-octane



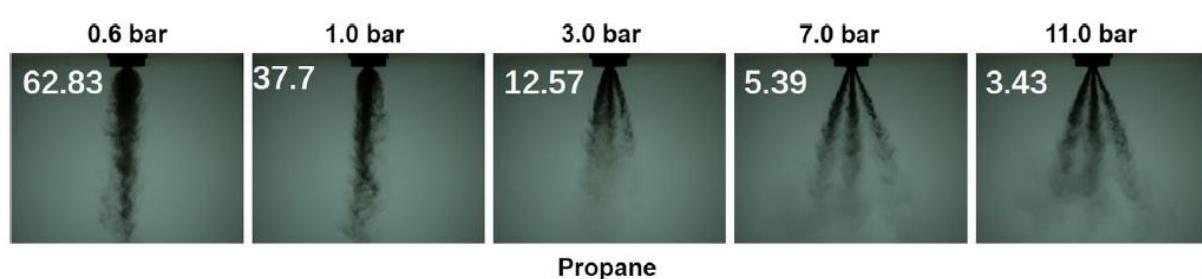
Previous optical work in a constant-volume chamber:

- 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

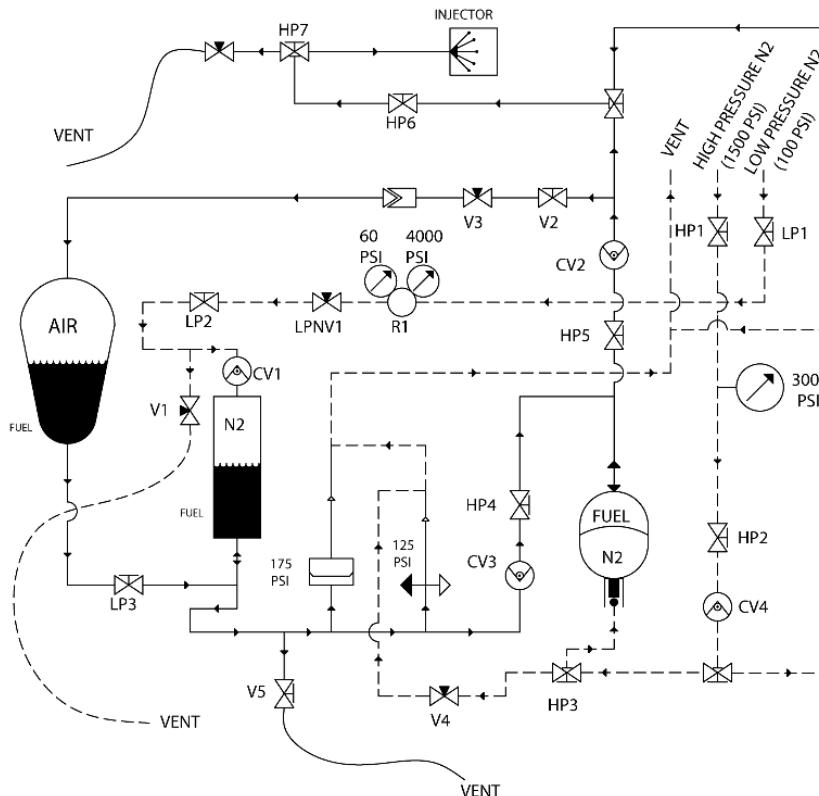


Li, Yanfei, Hengjie Guo, Zhifu Zhou, Zhou Zhang, Xiao Ma, and Longfei Chen. "Spray morphology transformation of propane, n-hexane and iso-octane under flash-boiling conditions." Fuel 236 (2019): 677-685.

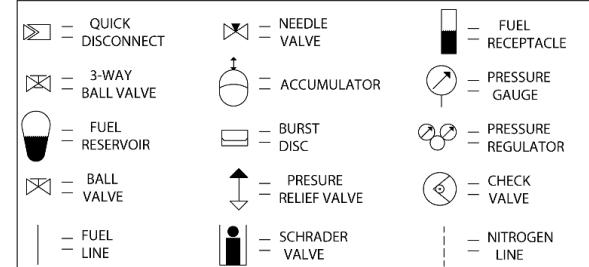
# Parallel propane and iso-octane fuel supply system allows quick switching between the two fuels



Iso-octane fuel system

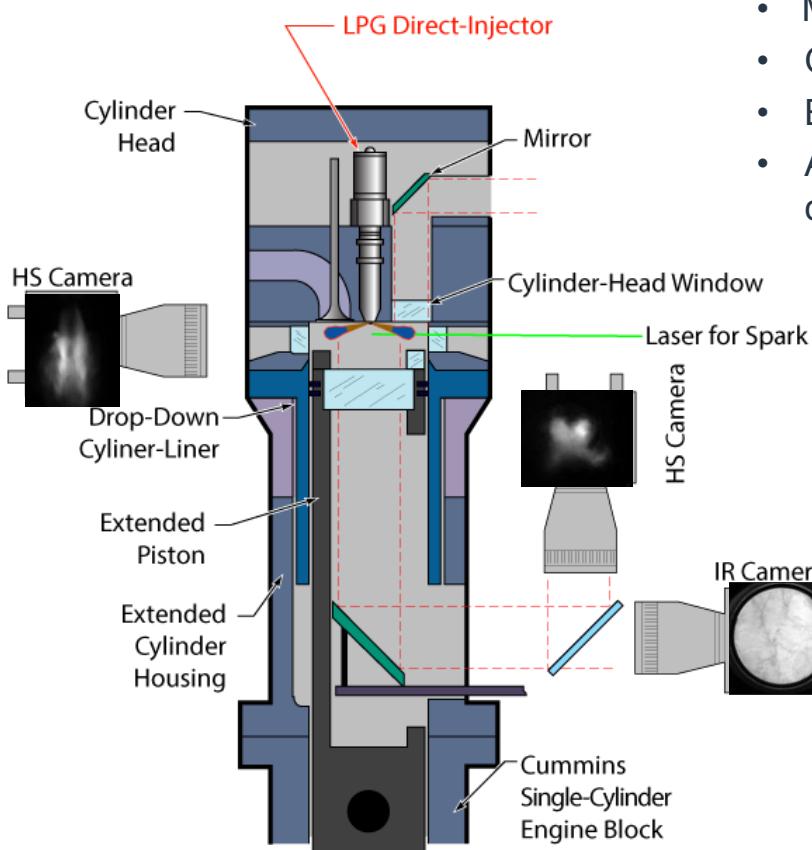


Liquid propane fuel system

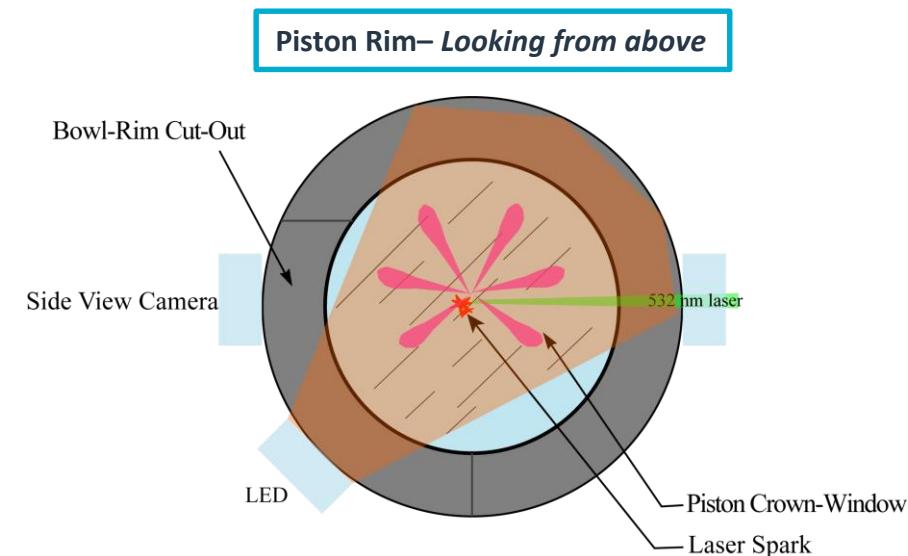


- The two fuel system can switch quickly from one to the other
- The two systems can run independently and separately

# High-speed Mie-scatter spray visualization from side and below; IR imaging of compression-heated fuel from below



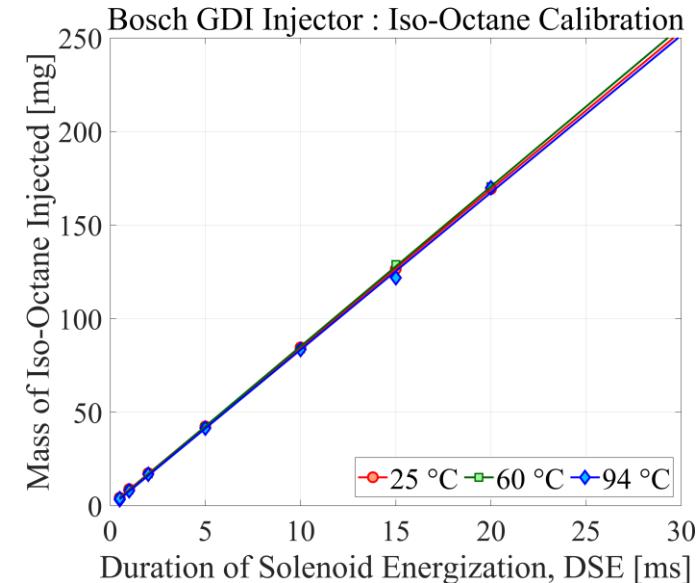
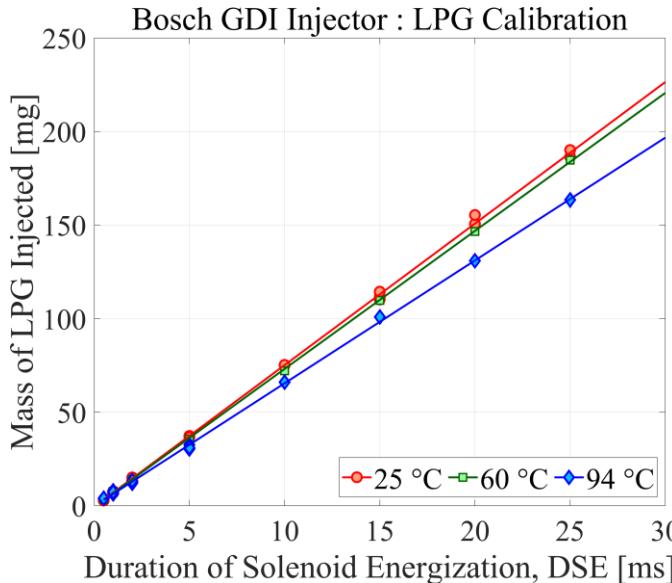
- Modified based on a HD single cylinder diesel engine
- Optical access to the engine combustion chamber
- Bosch HDEV-5 light-duty asymmetric 6-hole injector
- Asymmetric hole pattern is expected to resist spray collapse



| Combustion modes                                | Propane                             | Propane                             | Propane        | Propane        | Propane                    | Propane                  |
|---|-------------------------------------|-------------------------------------|----------------|----------------|----------------------------|--------------------------|
| Intake Temperature [C]                          | 60                                  | 60                                  | 60             | 60             | 60                         | 60                       |
| Intake Pressure [bar]                           | 1                                   | 1                                   | 1              | 0.5            | 0.3                        | 2                        |
| Intake O <sub>2</sub> [%] (N <sub>2</sub> dil.) | 0                                   | 0                                   | 0              | 0              | 0                          | 0                        |
| SSE [CAD]                                       | 214/181                             | 263/246                             | 60             | 60             | 60                         | 60                       |
| DSE [us]  | 26882/35959                         | 13441/17979                         | 26882/35959    | 12941/17889    | 7777/10661                 | 26882/35959              |
| DSE [CAD]                                       | 96.7752                             | 48.3876                             | 96.7752        | 46.5876        | 27.9972                    | 96.7752                  |
| ESE [CAD]                                       | 311                                 | 311                                 | 156.7752       | 106.5876       | 87.9972                    | 156.7752                 |
| Fuel Pressure [bar]                             | 100                                 | 100                                 | 100            | 100            | 100                        | 100                      |
| Coolant T [C]                                   | 30/90                               | 30/90                               | 30/90          | 30/90          | 30/90                      | 30/90                    |
| Global phi                                      | 1                                   | 0.5                                 | 1              | 1              | 1                          | 1                        |
| HS imaging                                      | 214:0.25:313.75/<br>181:0.25:280.75 | 263:0.25:362.75/<br>246:0.25:345.75 | 60:0.25:159.75 | 60:0.25:159.75 | 60:0.25:159.75             | 60:0.25:159.75           |
| IR imaging                                      | 304:4:360                           | 304:4:360                           | 304:4:360      | 304:4:360      | 304:4:360                  | 304:4:360                |
| notes   | ECN G (ab) at 310<br>CAD            | ac                                  | ECN G3 (ad)    | ECN G2(ae)     | iso-octane<br>collapse(af) | Propane non-<br>collapse |
| Case name                                       | ECN G@EOI                           | ECN G@EOI-Late                      | ECN G3         | ECN G2         | Low pressure               | High pressure            |

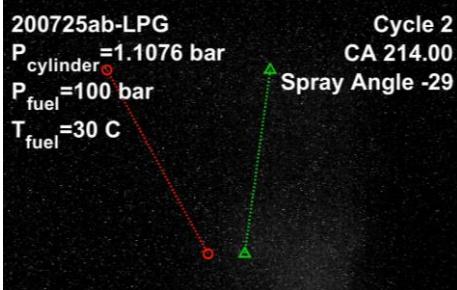
Iso-octane using the same intake conditions including SSE and DSE.

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

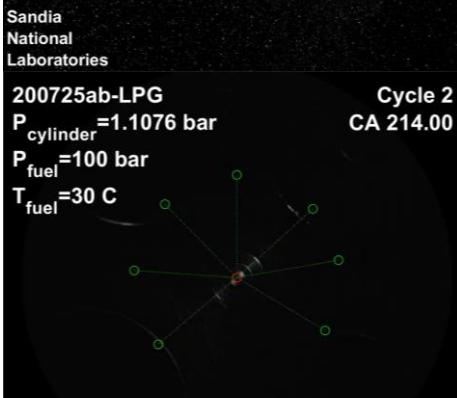


- The fuel temperature could significantly affect the mass flow rate from this injector for propane.
  - This is mainly due to the fact that the saturation pressure for propane is higher than 1 bar and propane is in gas phase at room pressure. The higher fuel temperature is causing more severe flash boiling and restricting the flow in the orifice.
  - However, for iso-octane is in liquid phase at 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.

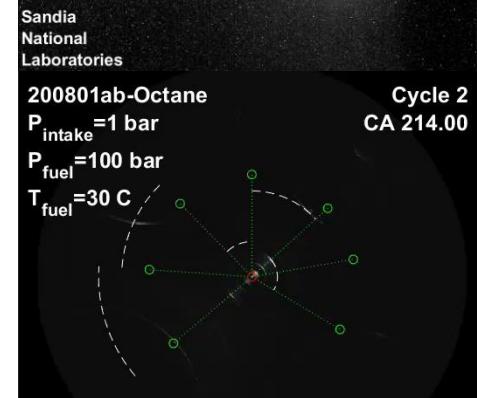
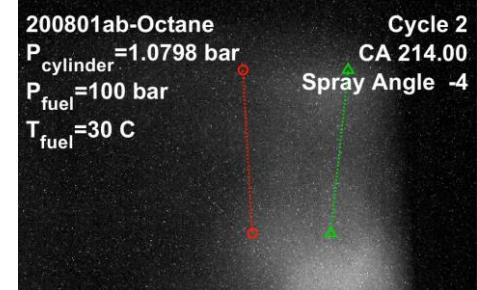
# Propane spray collapses at 1bar intake pressure and 30C coolant T, while iso-octane spray does not collapse and has greater liquid pen.



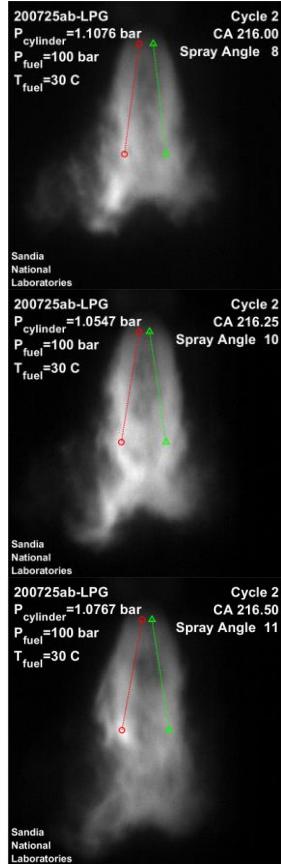
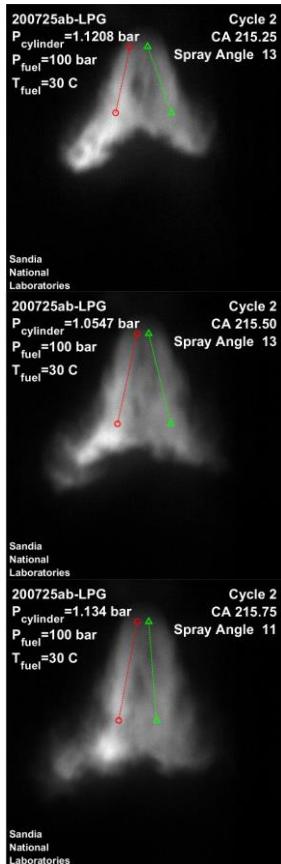
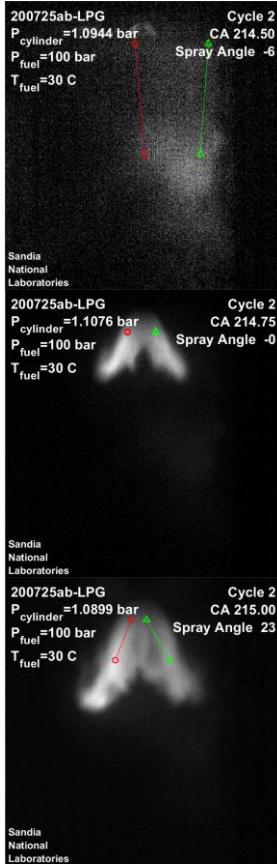
- Top row is the side view spray visualization; bottom row is the simultaneous bottom-view
- The red and green line on the side view indicate the spray axes.
- The propane spray collapses shortly after the start of injection but the iso-octane spray does not.



- In the bottom-view, the green lines are placed between sprays, and the red circle indicate the injector tip.
- The white curves indicate a threshold scattering intensity for each spray.

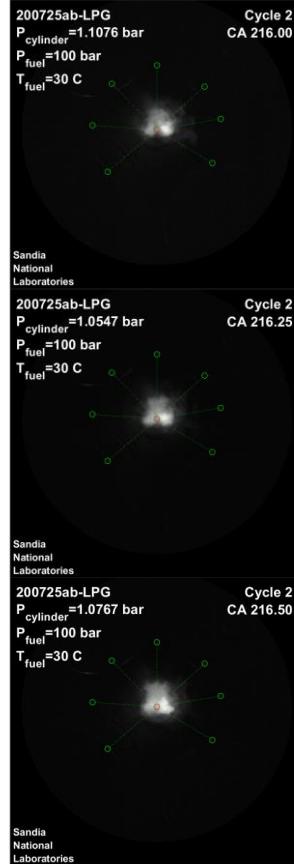


## ECN G@EOI side view

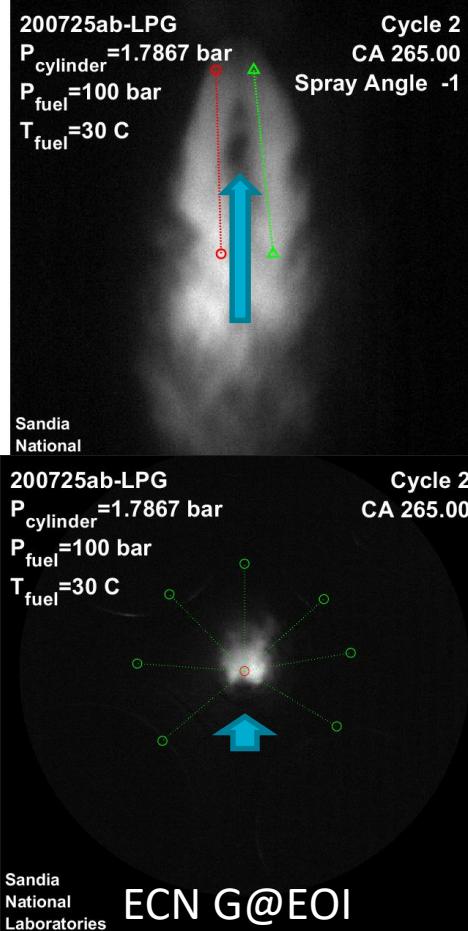


- The included angle (spray angle) of the spray pattern is computed between the red and green lines indicating the apparent spray axes
- The initial full included angle is greater than 20° after only 2 °CA, it decreases to less than 10° as the propane sprays collapse
- The bottom-view show that once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

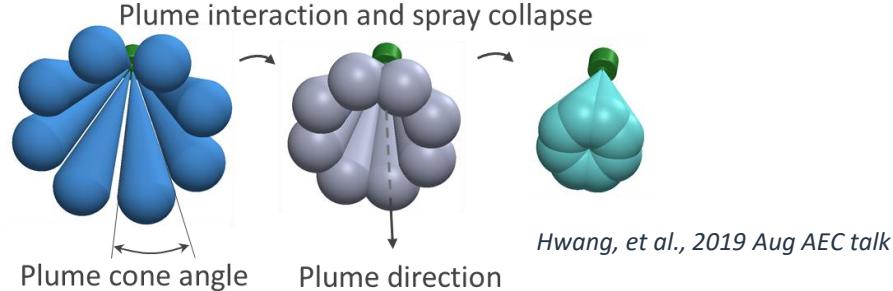
## Bottom view



# 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 [individual spray plume cone angle] 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”<sup>1</sup>.

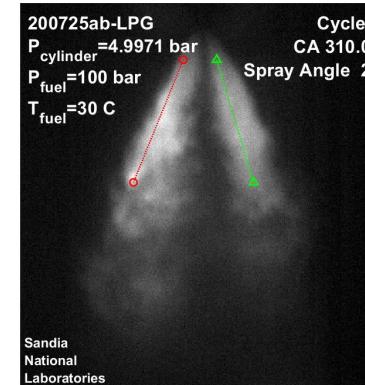
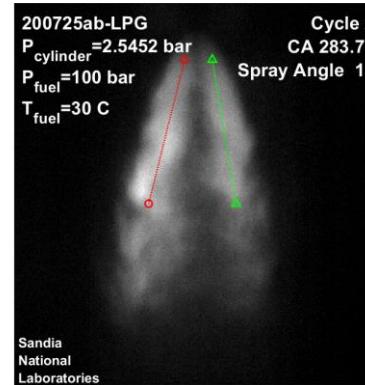
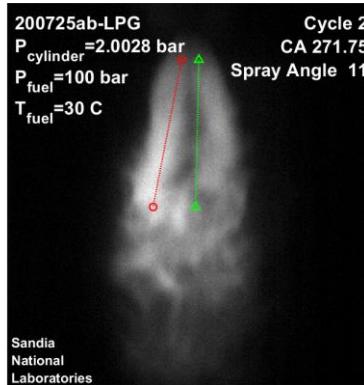
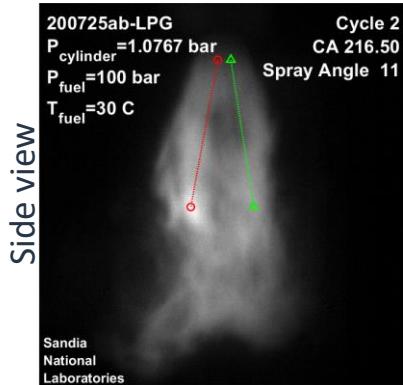
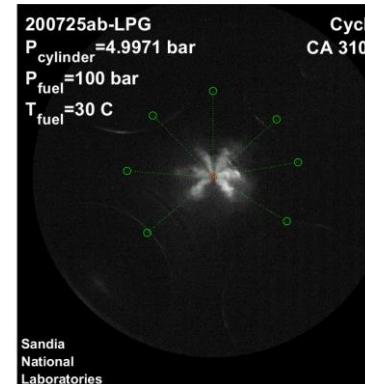
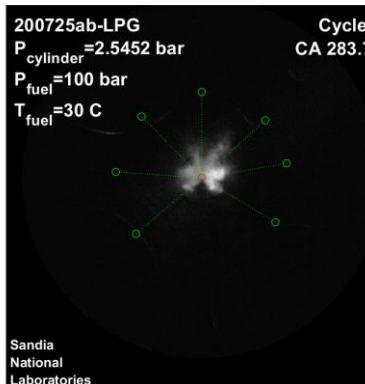
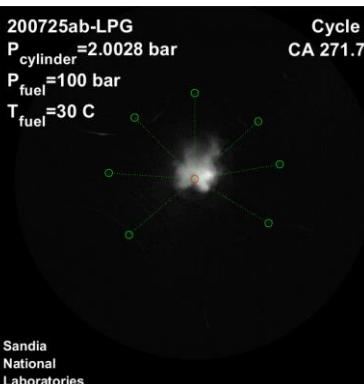
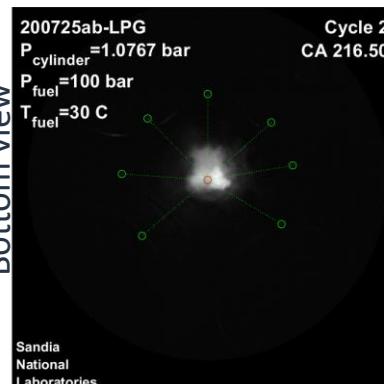


- Entrainment/recirculation is less confined with an asymmetric spray pattern, yet propane still collapses.

<sup>1</sup>. 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

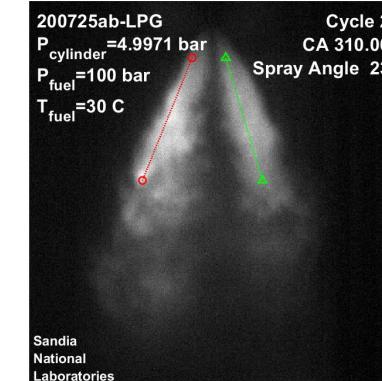
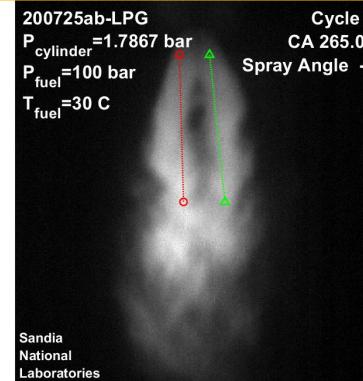
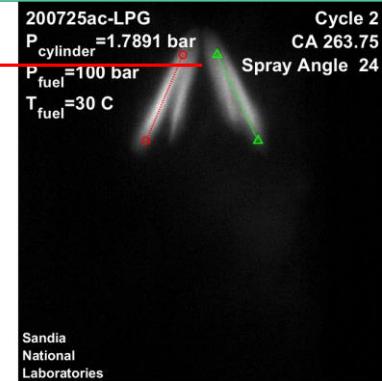
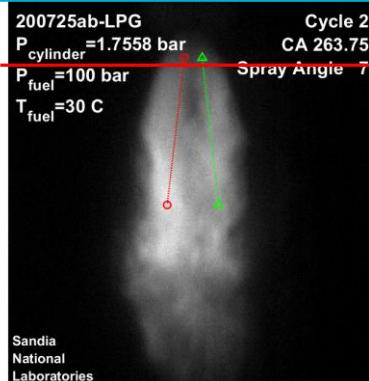
ECN G@EOI

ECN G@EOI  
Bottom view1 bar,  
collapse2 bar,  
collapse2.5 bar,  
collapse -> openECN G, 310 CAD  
non-collapse

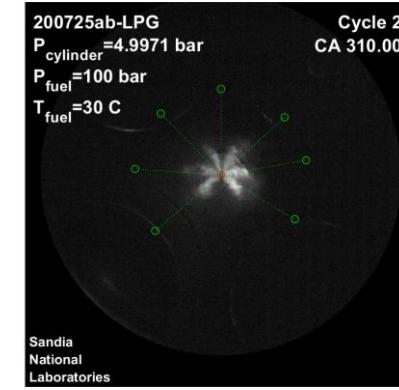
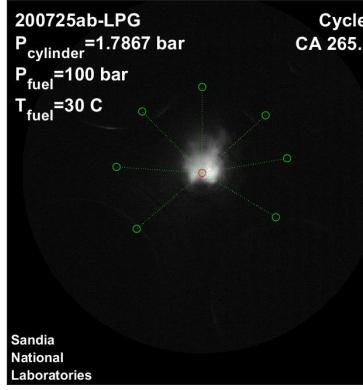
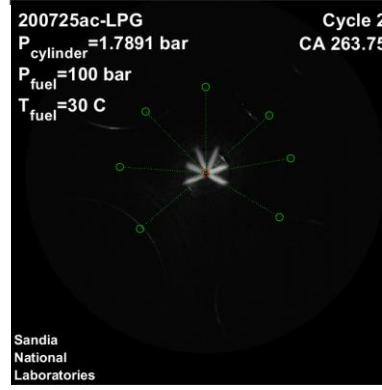
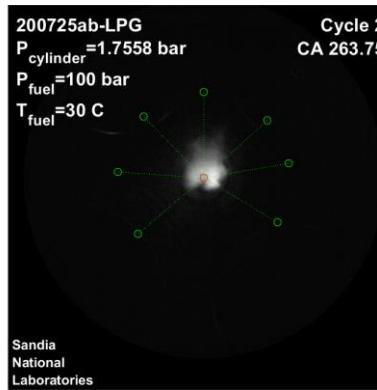
# Although a collapsed spray can open up, the threshold cyl. P is higher than for a later injection starting at a higher initial cyl. P



Side view



Bottom view



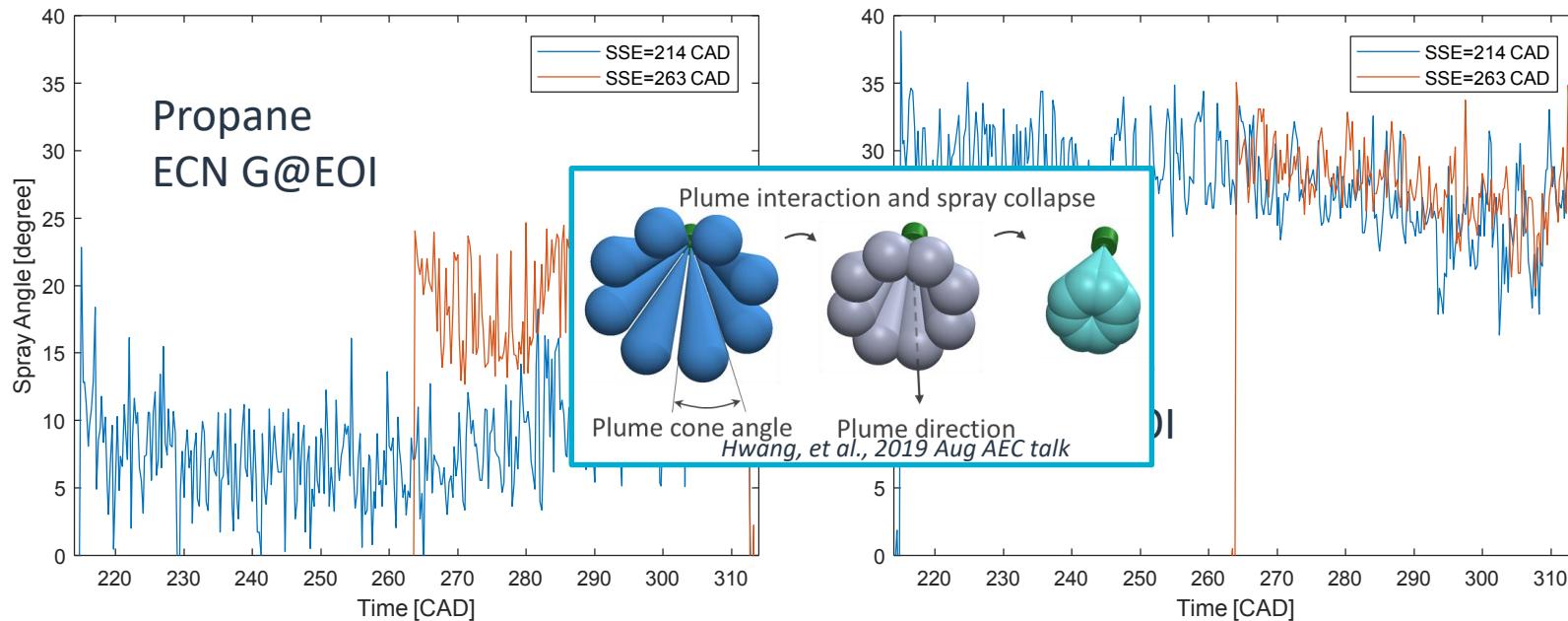
ECN G@EOI  
SSE 214, collapse

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

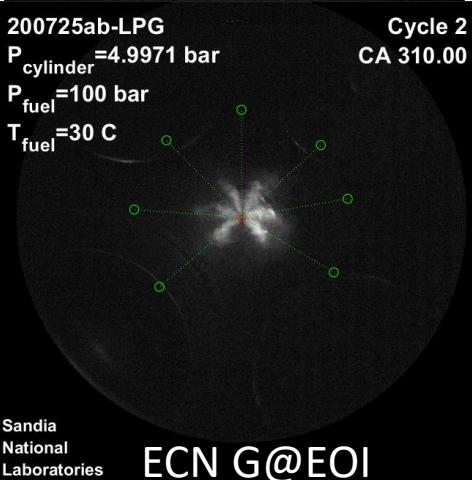
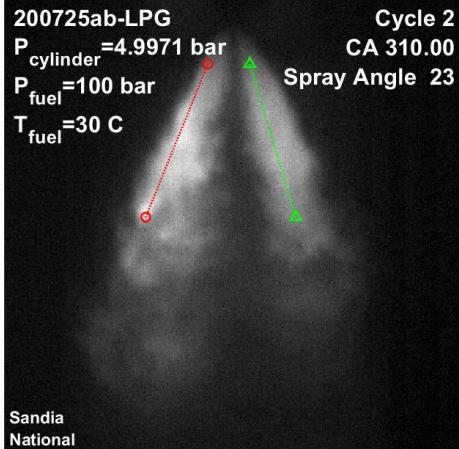
ECN G@EOI  
SSE 214, collapse

ECN G, 310 CAD  
non-collapse

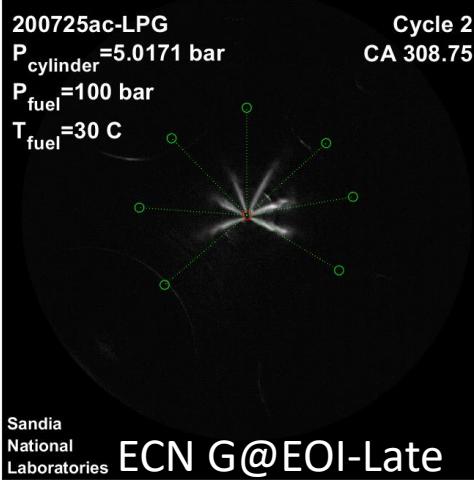
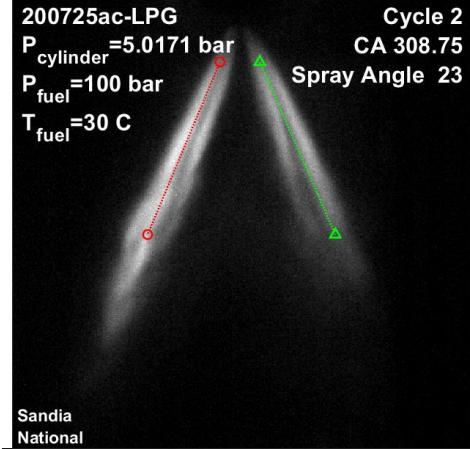
# Included angle for propane is decreased by spray collapse during intake stroke, while non-collapsing iso-octane is not affected



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.



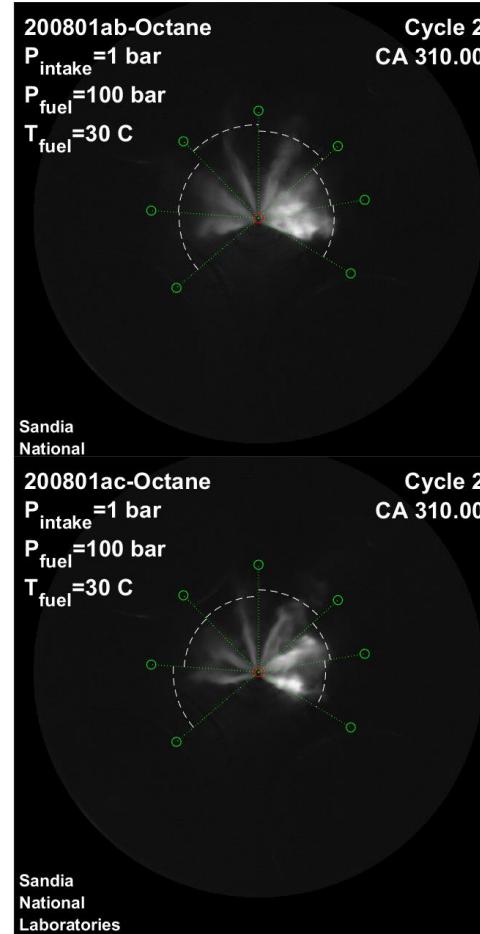
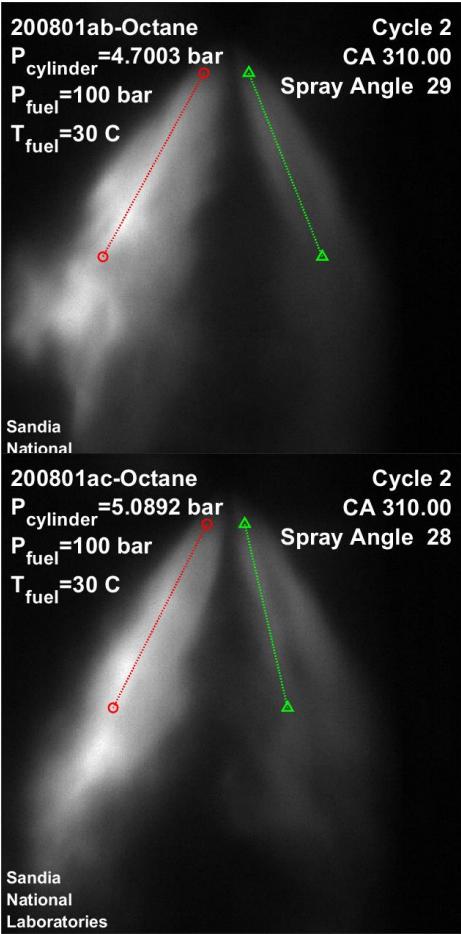
- The ambient temperature( $T_{am}$ ) is lower for earlier injection case on the left due to vapor cooling effect.
- The superheated degree ( $T_{fuel} - T_{am}$ ) is higher and this enhances propane flash boiling effect and causes the individual spray cone wider.



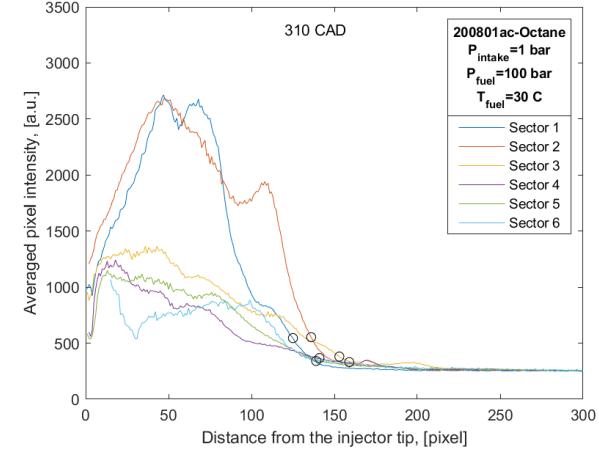
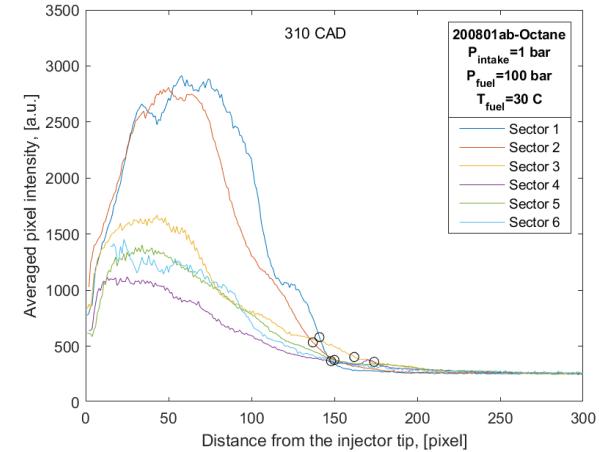
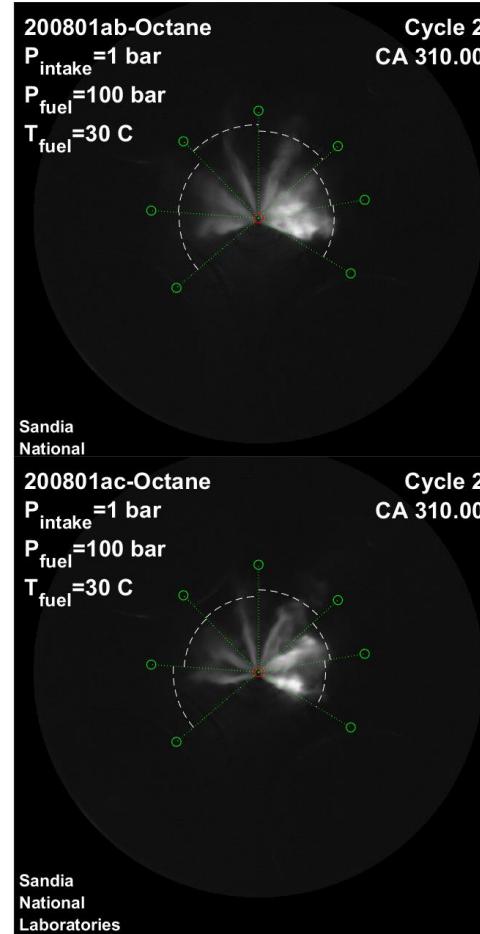
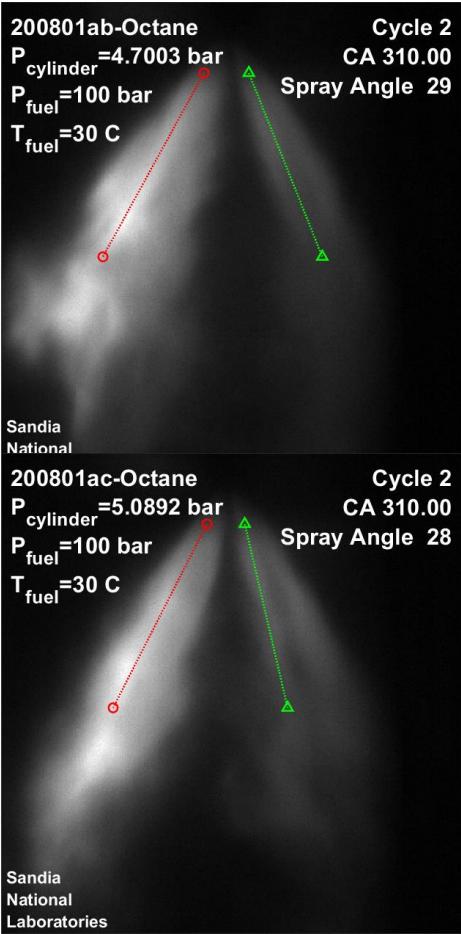
# Octane spray At ECN G condition: ECN G and ECN G-late has similar included angle but ECN G has slightly longer Mie-scattering length



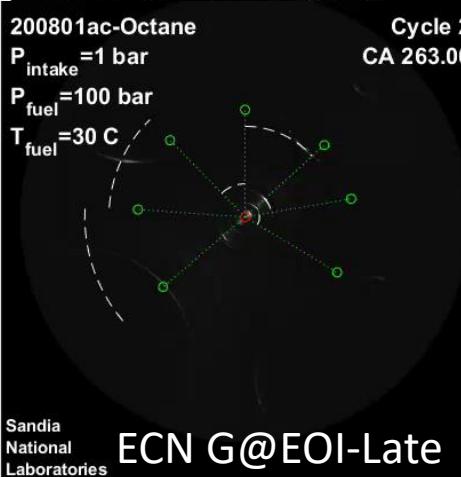
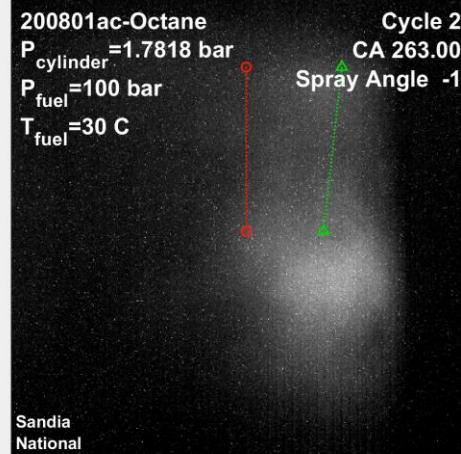
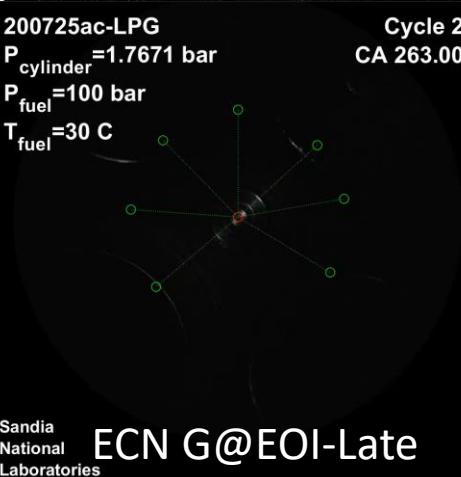
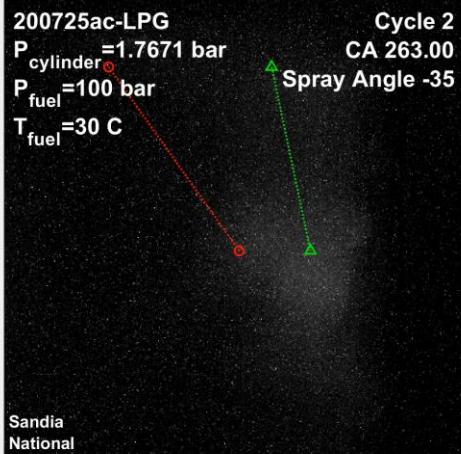
ECN G@EOI



ECN G@EOI-Late

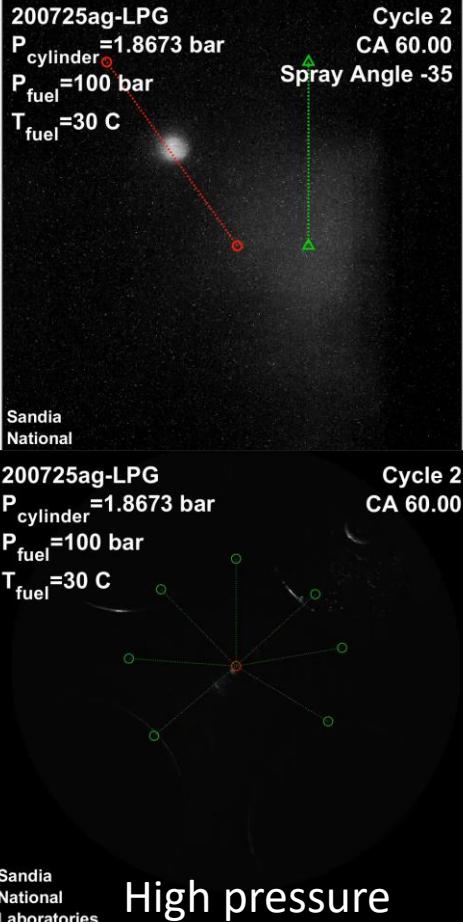


# No spray collapse for propane or iso-octane at 2 bar constant intake pressure, though the individual spray cone widened

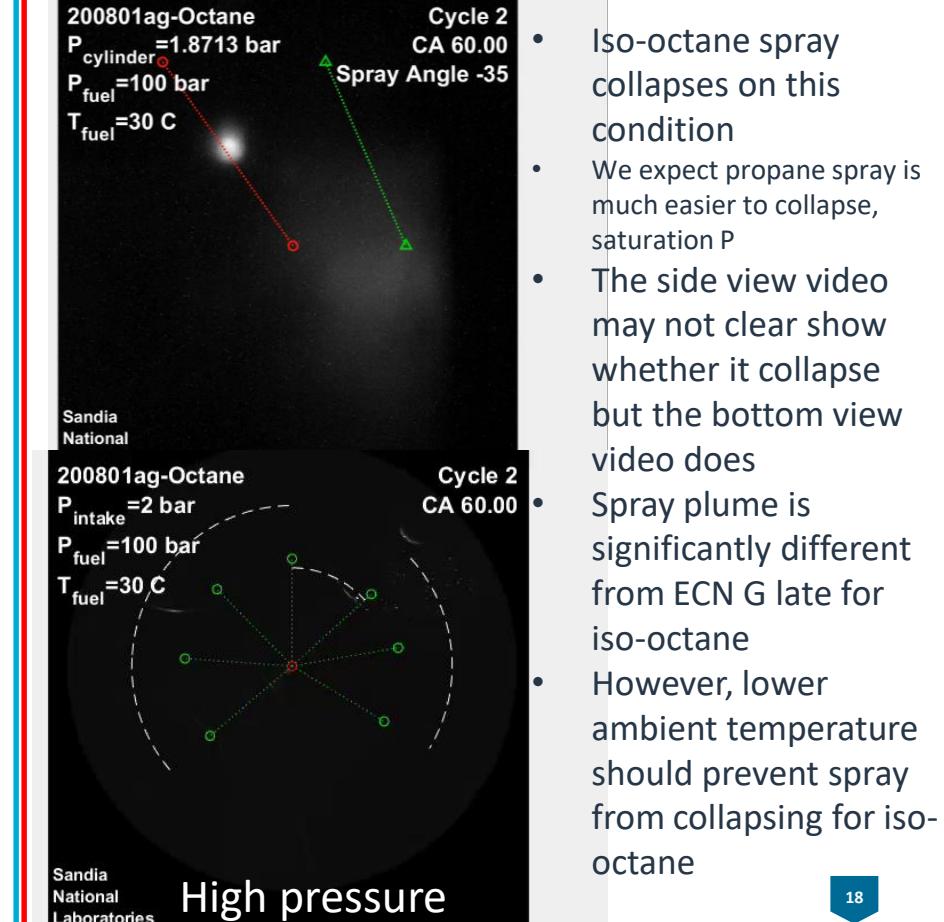


- Iso-octane spray doesn't collapse on this operating condition either.
- Iso-octane individual spray plume cone is wider
- On this condition, the cylinder pressure is 1.8 bar at SOI but increasing
- Please note the shape of iso-octane spray on bottom view

# No spray collapse for propane, while iso-octane spray appears to collapse at least partially 2 bar constant intake pressure



- Propane spray doesn't collapse at 2 bar pressure
  - Identical cylinder pressure as during compression for 1 bar intake, but no collapse here
- The superheated degree is higher than ECN G late injection, and the individual spray plume cone angles are bigger
- In this bottom-view, the sprays rotate likely due to swirling intake flow



- Iso-octane spray collapses on this condition
- We expect propane spray is much easier to collapse, saturation P
- The side view video may not clearly show whether it collapses, but the bottom view video does
- Spray plume is significantly different from ECN G late for iso-octane
- However, lower ambient temperature should prevent spray from collapsing for iso-octane

# One potential explanation for the iso-octane spray collapse at 2 bar is condensation-induced collapse

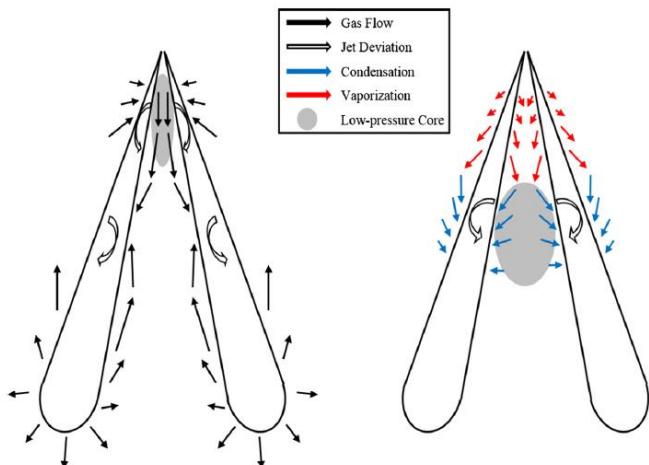


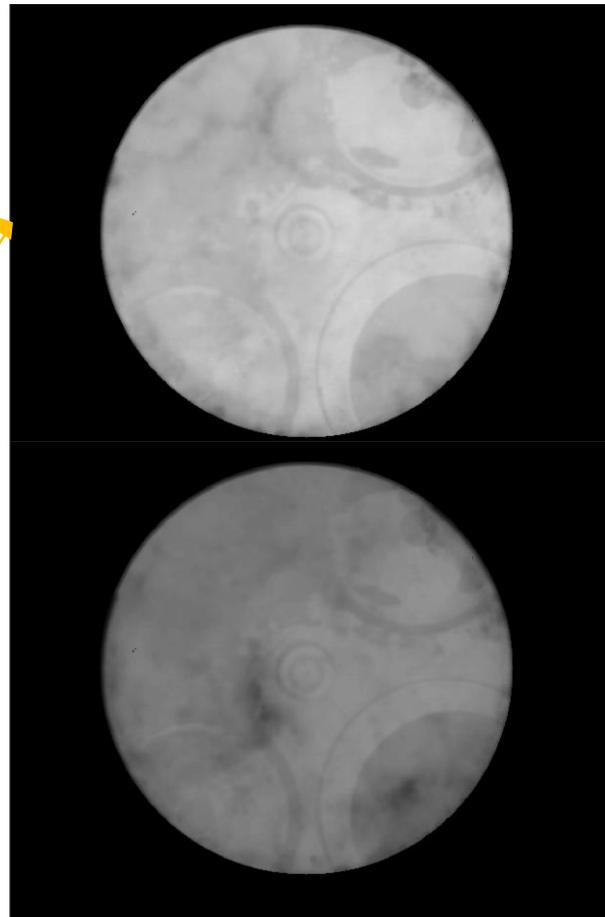
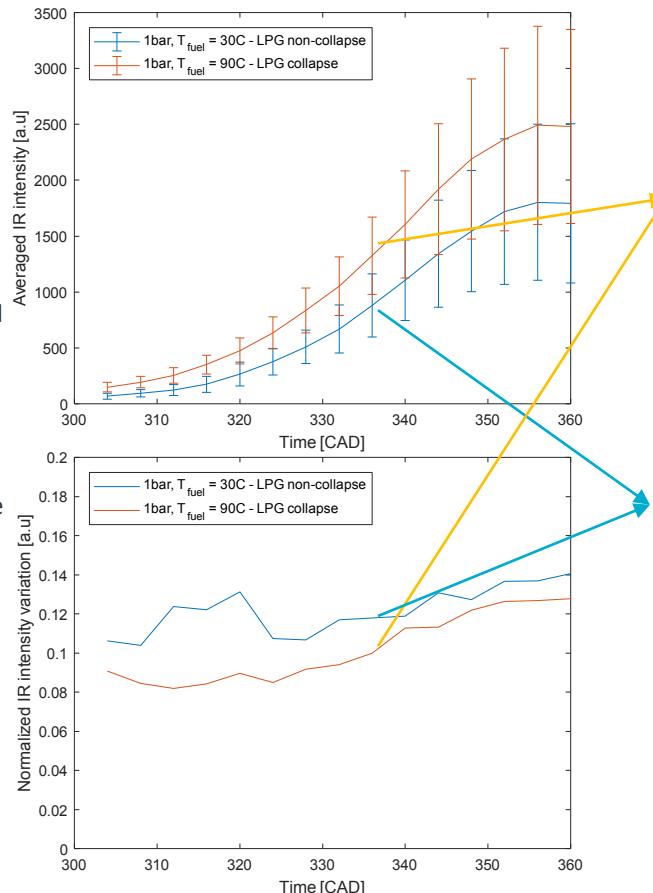
Fig. 10. Mechanisms of the jet-induced spray collapse (left) and the condensation-induced spray collapse (right).

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 propane show some degree of less homogeneity for collapse condition than non-collapse at spark timing

- 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, propane 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 absolute 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.

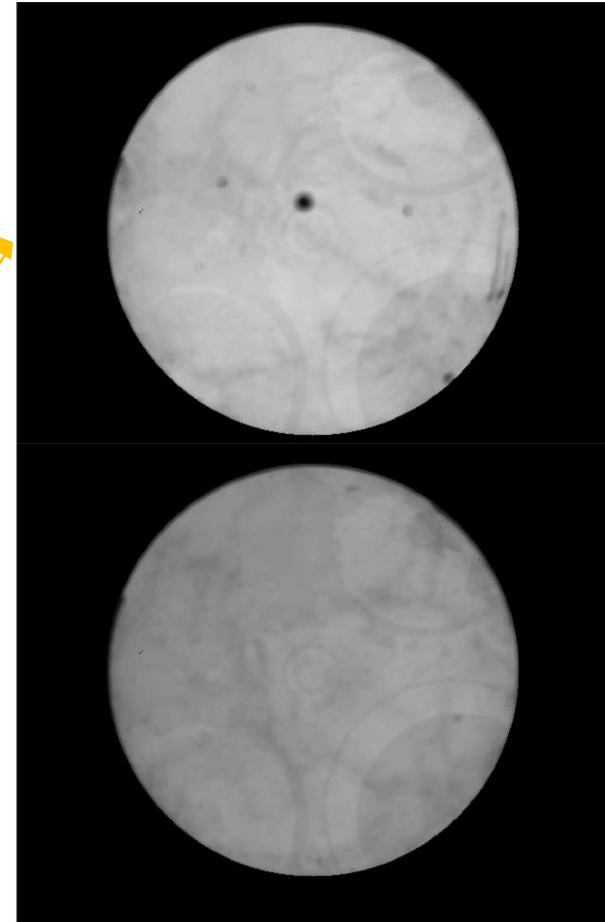
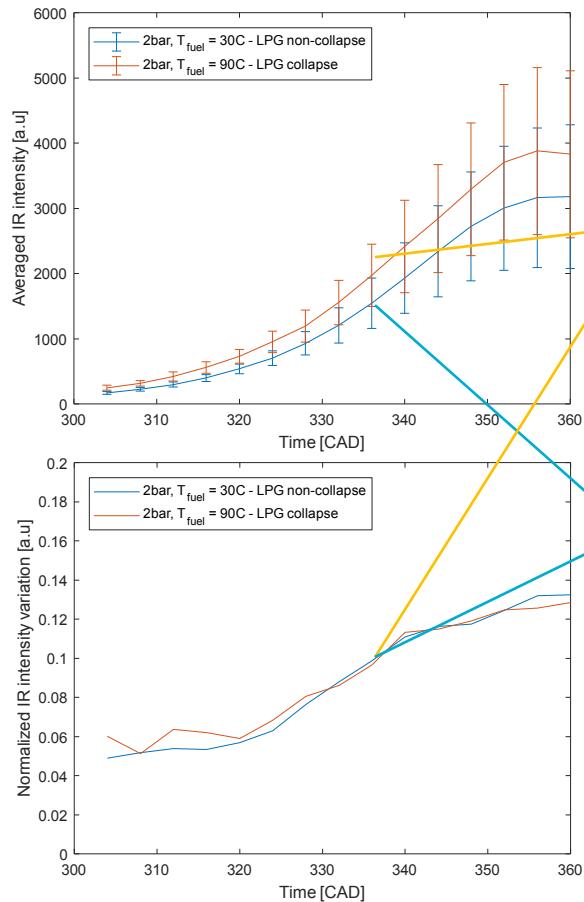


ECN G-Late  
SSE=263  
90C fuel T  
Collapse

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

# IR images of propane show identical homogeneity for collapse condition and non-collapse at spark timing

- Both cases have same intake condition at 2 bar, propane 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 pressure  
SSE=60  
90C fuel T  
Collapse

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

# In progress: contrast propane and iso-octane spark-ignition combustion with and without spray collapse

- 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 2<sup>nd</sup>.
- It wasn't clear whether the window crack is due to laser drill in the window.
- We do get the laser spark and have a few fired test runs with iso-octane.
- We will replace the liner window and continue to fire the engine with propane DI.



# Evolving cylinder pressure in engines affects dynamics of propane and iso-octane spray collapse differently than when ambient is cons.

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- Propane DI fuel system demonstrated in heavy-duty optical engine
- Propane DI injection flow rate decreases with increasing coolant while iso-octane injection rate is unchanged
- Propane spray collapse occurs at lower fuel temperature and lower intake pressure than iso-octane due to its higher saturation pressure
- Asymmetric spray pattern with open sector shows spray collapse under some conditions, especially with propane
- Propane injections that collapse during the intake stroke can later open up during the compression stroke
- For a single injection, when a propane spray collapse initially, it tends to stay collapsed even at transient conditions then a new starting injection would not collapse
- For some higher cylinder pressure conditions, iso-octane sprays collapse at least partially while propane sprays do no. Condensation-induced collapse might be at play
- Initial IR images do not show large difference in mixing among collapsing or non-collapsing sprays for very long injections utilized here, and in some cases a collapsed spray may yield a more homogeneous charge

# Acknowledgements

- Dr. Paul Miles, *CRF Sandia* – Department manager
- Dave Cicone, *CRF Sandia* – Engine hardware support
- Keith Penney, *CRF Sandia* – Electronics support
- Gurpreet Singh, *DOE EERE* – Funding support
- Michael Weismiller, *DOE EERE* – Funding support
- Kevin Stork, *DOE EERE* – Funding support

This research was sponsored by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE). Optical engine experiments were conducted at the Combustion Research Facility, Sandia National Laboratories, Livermore, CA. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.





**Thank you for your attention!**