Development of Heavy-Duty Liquid Petroleum Gas Engine with Near-Diesel Engine Efficiency using Advanced Combustion Strategies

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Motivation/Background

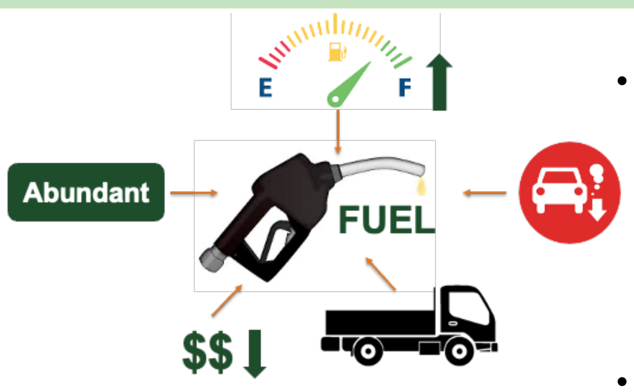


Figure 1: Properties of an Ideal Fuel.

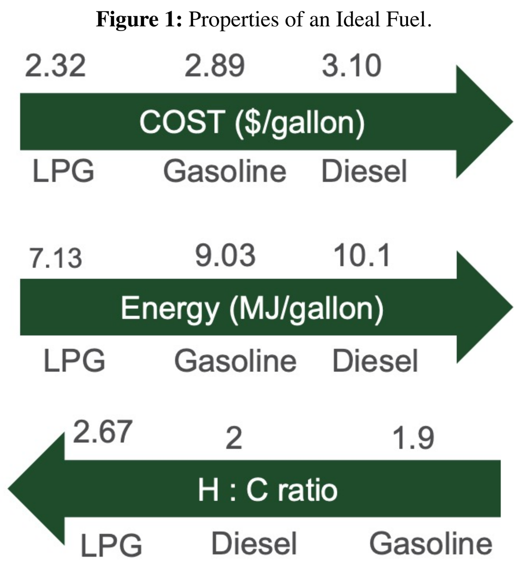


Figure 2: Comparison between LPG And Common Fuels.

- Internal combustion (IC) engine research focuses on the improvement of fuel economy and the reduction of the tailpipe emissions of CO_2 and other regulated pollutants.
- Direct-injection (DI) and alternative fuels such as liquefied petroleum gas (LPG) are promising solutions.
- LPG represents a practical and economical solution for fueling the United States' heavy-duty transportation sector. However, before widespread adoption can occur, energy conversion efficiencies for LPG engines must achieve values comparable to those seen in diesel engine platforms.

To date, limited information is available regarding the spray dynamics of LPG at engine relevant conditions. On the global market LPG composition can vary dramatically, leading to even more insufficient data. The successful completion of the project will allow future research to use the finely tuned LPG spray model to develop a heavy-duty LPG engine with diesel like efficiency.

Research Goals

Figure 3: Proposed Overarching approach to realize "near-diesel" efficiencies for LPG engines.

Problem: Low fuel economy and significant tail gas emissions of heavy-duty diesel engines. Engine Knock and Misfires are challenges in achieving high engine efficiency.

Solution: Direct Injected Spark Ignited Liquified Petroleum Gas Engine Design using Advanced Combustion Techniques involving C-EGAI, Stratified Combustion by DI, EGR, Real time Algorithms, Flame Propagation

Overarching Goal: To address fundamental limitations in achieving near diesel efficiencies in heavy duty on-road liquefied petroleum gas (LPG) engines.

Device Goal : To increase the peak torque efficiency of a Cummins X-15 SCE LPG engine to 44%.

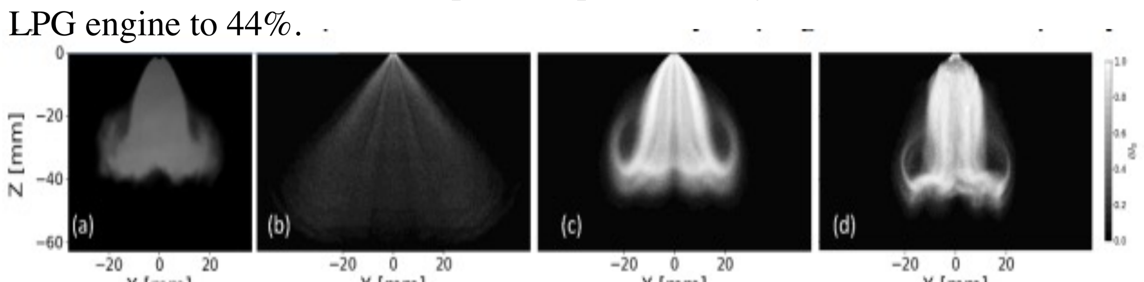


Figure 4: ECN's spray-G injection of flashing iso-octane at Pinj = 200 bar, Tinj = 363 K, Pamb = 20 kPa. Comparison between (a) experimental DBI image and CFD light attenuation images: (b) standard ROI L-E approach, (c) one –way coupling and (d) one-way coupling with Lagrangian parcel flash boiling vaporization term [1].

Spray Modelling: High fidelity nozzle flow simulation to study internal flow dynamics and mixing

Need for Validation:

High Volatility and low Viscosity of LPG
Varying Global Composition
Subcritical and Supercritical behavior
Boundary Condition

Research Goal: To develop an experimental setup to verify and tune DI LPG engine simulation

Methods/Experimentation

Techniques: High Speed Schlieren, Mie Scattering, and Planar Laser Induced Fluorescence

Conditions: T_{amb} = 380 K, P_{amb} = 2 to 10 bar, T_{fuel} = 363 K, P_{inj} = 200 bar, 500 μsec ASI

Measurements: Penetration lengths, spray angles, rate of mixture formation for a range of chamber conditions, fuel compositions, and early to late injection techniques

High Pressure Spray Chamber Specifications:

- Max Temperature: 745 K
- Max Pressure: 1000 psi
- Fuel Stratification capabilities
- 3-Way Optical access; Quartz Windows (6")
- Integrated cooling jacket for injector tip
- Engineered flange to incorporate Bosch HDEV 5.2 (P_{max} = 350 bar) and Spray-G
- Configurable Injector Driver : Woodward's Large Engine Control Module (LECM)

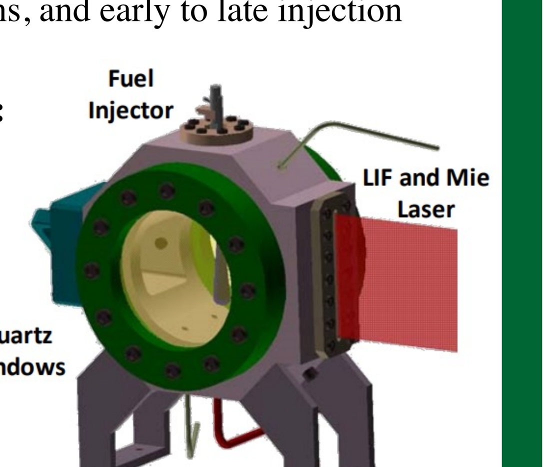


Figure 5: HPSC design.

The High Pressure Spray Chamber (HPSC) (1) in figure 7, is controlled to hold engine like pressure and temperature conditions. The Bosch BMW 335i fuel injector (3) is driven using Woodward's Large Engine Control Module (LECM) (2). The fuel is pressurized using a syringe pump (4) to about 2000 psi.

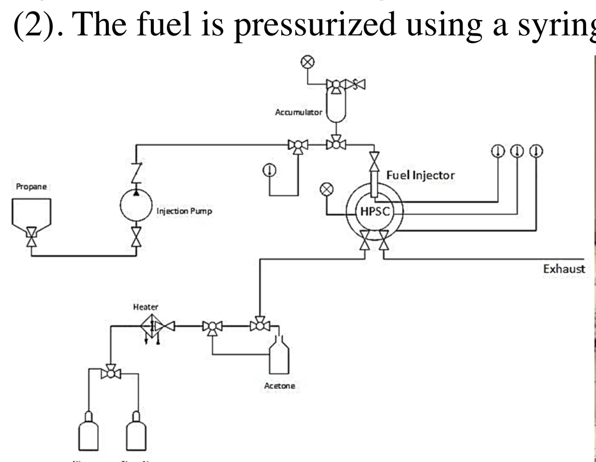


Figure 6: Piping and Instrumentation Diagram of the HPSC system.

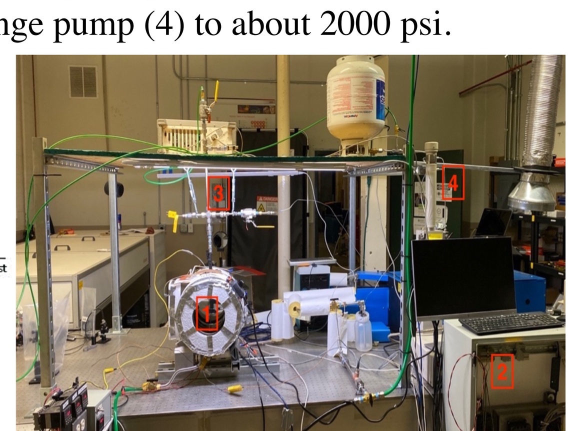


Figure 7: The High-Pressure Spray Chamber System Setup Assembly.

Spray Imaging Techniques

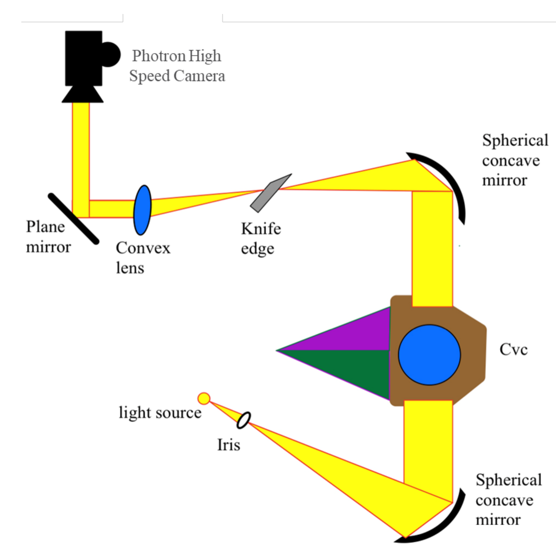


Figure 8: Schlieren system schematic .

Schlieren Imaging

Schlieren is a shadowgraph imaging technique used to visualize density gradients, spray penetration length, spray angle, and fuel mixing. This real time high-speed imaging technique is used to visualize the flow in a medium.

Schlieren Specifications:

- 200 Lumens White Light Emitting Diode (1 in figure 10)
- 6" Parabolic Mirrors (f = 0.75 m) (2&3)
- High Pressure Spray Chamber (4)
- Knife-Edge (5)
- Photron FASTCAM SA5 High Speed Imaging Camera (fps_{max} = 1,000,000) (6)

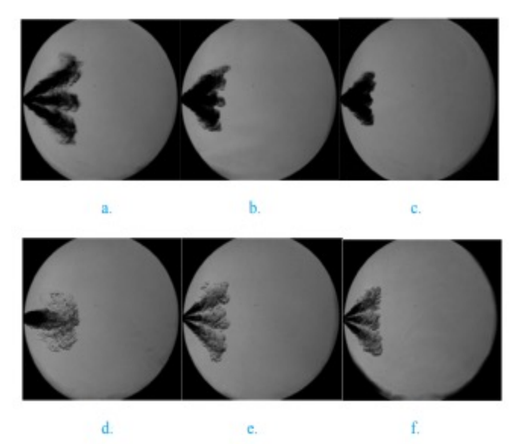


Figure 9: Schlieren Imaging at a CVC temperature of 380 K, and 500 μs ASI at a CVC pressure of Iso-octane: (a) 2 bar (b) 6 bar (c) 10 bar Propane: (d) 2 bar (e) 6 bar (f) 10 bar [2].

Many Schlieren studies for propane and iso-octane have been performed throughout literature, like the one seen in the figure on left, this allows comparison with literature for fine tuning of Spray Chamber Setup. Schlieren images highlight the presence of density gradients and thus can mark both liquid and vapor regions, but the phase boundary is often difficult to identify.

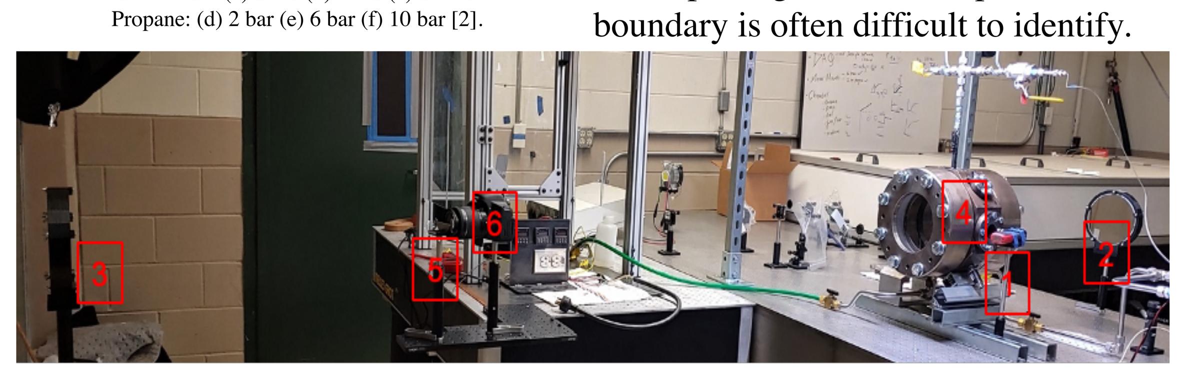


Figure 10: Assembled Schlieren Setup.

Simultaneous PLIF and Mie Scattering

Due to limited scope of Schlieren Imaging, following Spray Imaging Techniques are used to clearly differentiate between fuel vapor and liquid regions to study the in-cylinder fluid motion during internal combustion in an engine.

Techniques:

Mie Scattering : Elastic Light Scattering Technique used to measure Liquid Penetration through a medium
From literature: LPG requires 100 mJ of 532 nm (green) light beam

Acetone PLIF : Planar Laser Induced Fluorescence technique to excite the acetone doped chamber to measure the vapor penetration medium
From literature: Acetone requires 85 - 100 mJ of 266 nm(Ultra-violet) light beam

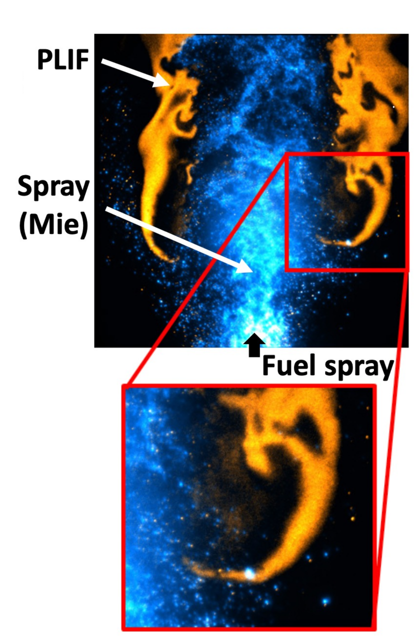


Figure 11: PLIF/Mie Scattering measurements of Jet fuel [3].

Figure 11 on left was taken for jet fuel flames, the blue regions represent the liquid fuel atomizing to form droplets while the orange regions are from OH fluorescence and mark the location of the flame. With this data co-locating the fuel droplets and the flame, the number of droplets penetrating the flame was quantified which highlights the importance of these interactions on lean blowoff limits.

Similar Techniques will be used like the above study, to quantify both spray and vapor penetration, important toward the validation of both atomization and evaporation LPG spray sub-models.

PLIF and Mie Scattering Specifications:

- A Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG) laser capable of producing 5J of 532nm is used as a light source for Mie Scattering.
- To perform PLIF experiments for acetone, a Fourth Harmonic Oscillator is used to convert the green output from the laser, partially into Ultra-violet light.
- An Andor ICCD CMOS High Speed Camera and Photron FASTCAM SA5 Camera are used for simultaneous frame straddling technique.
- Internal and external timing generators will be used to synchronize both cameras, injector, and laser.
- Flame straddling technique will be used to collect both Mie and PLIF measurements
- The Schematic for the HPSC setup to carry out the Mie and PLIF Imaging techniques is shown below in figure 12.

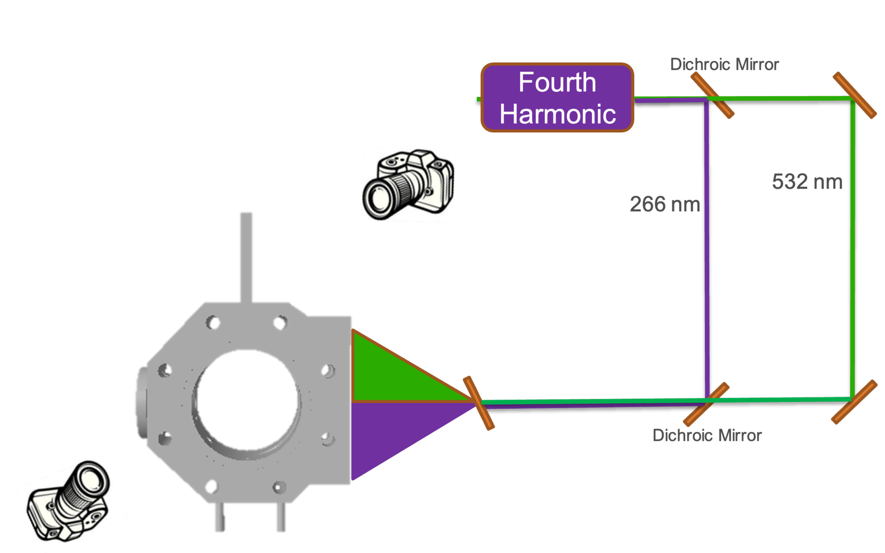
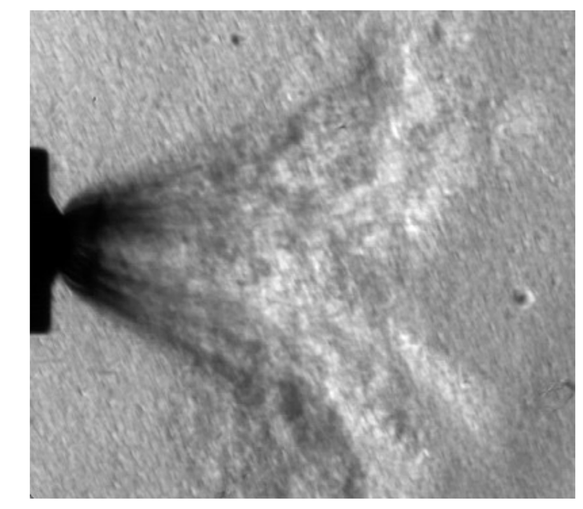


Figure 12: Mie and PLIF Design Schematic.

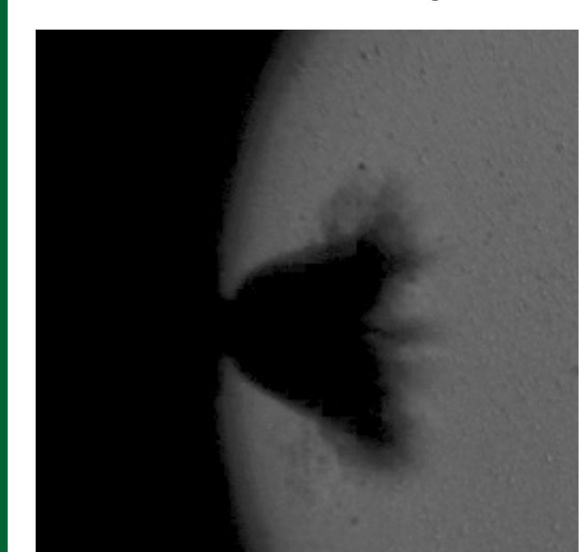
Results

One of the principal requirements for the Computational Spray Modelling is that the Bench-top Spray Testing Setup is able to hold the boundary conditions consistently and reliably. These boundary conditions involve the chamber (often called ambient) temperature, chamber pressure, injection timing and duration of the fuel, temperature at the injector tip, fuel pressure and temperature. The HPSC is currently able to reliably meet and consistently hold these conditions which can then be sent to Argonne National Lab (ANL)to be set as the boundary conditions for spray modelling.



Spray Conditions.
Fuel: Propane
T_HPSC Block : 86 °C
T_gas in HPSC : 112 °C
P_HPSC : 0.05 psig
Injector : BMW 335i EU6
T_inj tip (T_fuel) : 107 °C
P_inj : 100 psig
Injection Duration : 500 μ-seconds
Photron Camera Speed : 50000 frames per second

Figure 13: Collected High-Speed Propane Schlieren Image 1.



Spray Conditions.
Fuel: Propane
T_HPSC Block : 55 °C
T_gas in HPSC : 70 °C
P_HPSC : 0.05 psig
Injector : BMW 335i EU6
T_inj tip (T_fuel) : 30 °C
P_inj : 1600 psig
Injection Duration : 500 μ-seconds
Photron Camera Speed : 30000 frames per second

Figure 14: Collected High-Speed Propane Schlieren Image 2.

The images above are snapshots from recorded High-Speed Schlieren Videos. These Images show the Schlieren Image of propane spray injected at the mentioned the conditions.

In figure 13, the darker region near the fuel injector nozzle tip (left) are the liquid propane fuel droplets, where as the spray farther away from the nozzle is vaporized fuel. From these one can also see the spray plumes(jets) penetrating the chamber and collapsing by mixing into the ambient gas inside the HPSC as the spray gets further from the nozzle.

Conclusion

The Schlieren Images shown above our comparable to the ones recorded by Lacey et al. in figure 9. The Schlieren results recorded show the general behavior of the LPG spray inside the HPSC. But the Schlieren Imaging technique needs to be finely tuned for sharper and clearer images which show the plume-to-plume interactions distinctly before the collected data can be used for Computational Spray Modelling by Argonne National Lab. The quality of these images need to be enhanced by fine tuning and aligning the optical setup shown in the schematic in figure 8 and 10.

Future Work

Simultaneous PLIF and Mie Scattering:
Post Schlieren Imaging and the installation of the Fourth Harmonic Generator, the Simultaneous Mie Scattering Imaging and Acetone Planar Laser Induced Fluorescence Imaging Techniques will be used to record the spray behavior involving, but not limited to, liquid penetration length, vapor penetration length, spray angles, liquid and vapor phase region, etc. for a variety of boundary conditions and LPG fuel composition. These measurements will then be used to verify and finely to the Computational LPG Spray Models.

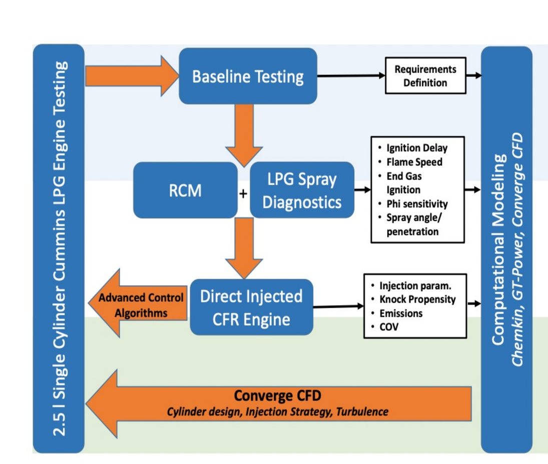


Figure 15: Integrated research approach over 3-year project duration.

A second outcome from the HPSC tests will be to aid the identification of injector/nozzle designs and operational strategies that will lead to optimal performance when applied to the Cummins X15 SCE. Modified injectors informed by bench testing will be examined in the HPSC to confirm performance and to provide key data to ANL for model development. HPSC testing will be carried out to identify limitations in injection pulse widths, number of injections, and injection event frequency. These data will be important to constrain SCE CFD efforts which will explore fuel injection rate shaping on fuel stratification. Additionally, these tests will provide important intuition regarding injection strategies on fuel mixing and fuel penetration to enable more rapid convergence on identifying optimal injection strategies with CFD.

References

[1] Nocivelli, L. et al (2019) Proc. of ASME ICEF 2019, ICEF 2019-7258
[2] Lacey, Joshua, et al. Optical characterization of propane. No. 2016-01-0842. SAE Technical Paper, 2016.
[3] Alsulami, R., et al. (2020) Proceedings of the Combustion Institute.

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