From Optical Spray Diagnostics to Peripheral Fuel Injection (PeFI): Advancing Diesel Combustion for High-Efficiency and Low-Emissions

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The University of Alabama

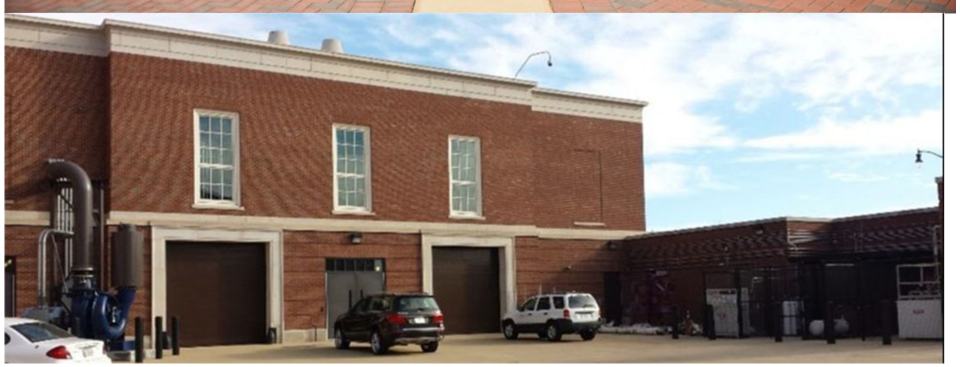
Plenary Lecture, Monday, May 13, 2024
2024 Spring Technical Meeting of the Central States Section of The Combustion Institute

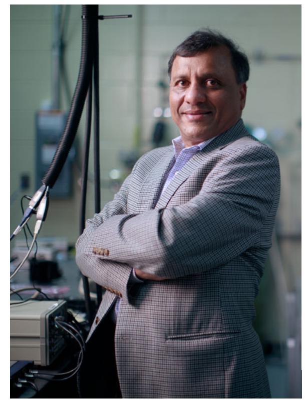
COMBUSTION LABORATORIES
THE UNIVERSITY OF ALABAMA
LOW EMISSIONS • HIGH EFFICIENCY • FUEL FLEXIBILITY

First, Thank You to the Organizing Committee for invitation and this opportunity

- I have had the opportunity to engage with the CSSCI for the past 30 years in various roles.
- Nice to see many long-time friends as well as new friends and colleagues.
- I am happy to note that CSSCI is making great progress in these supposedly challenging times.
- I hope my presentation today will offer optimism for combustion science and technology and show how combining these two seemingly disparate efforts can provide innovative solutions to meet the energy needs of today and tomorrow.

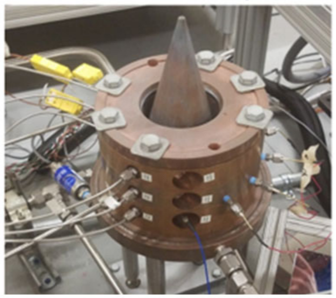
Engine and Combustion Laboratory (ECL) at The University of Alabama

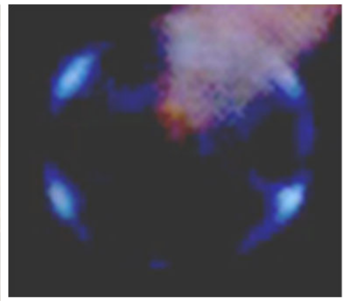




Combustion Research

Rotating Detonation Combustion

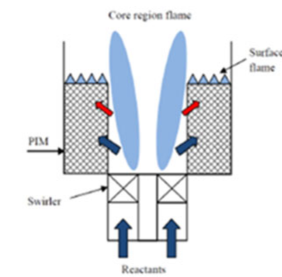




Passive Control of Thermoacoustics

Visual Image with PIM

Flow schematic with PIM



3D Printed porous insert

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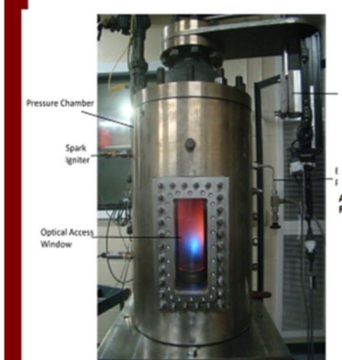
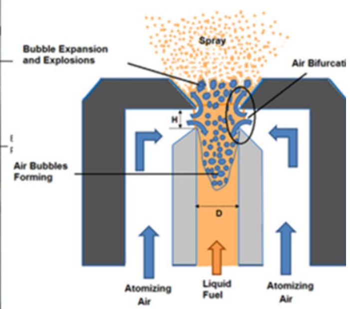
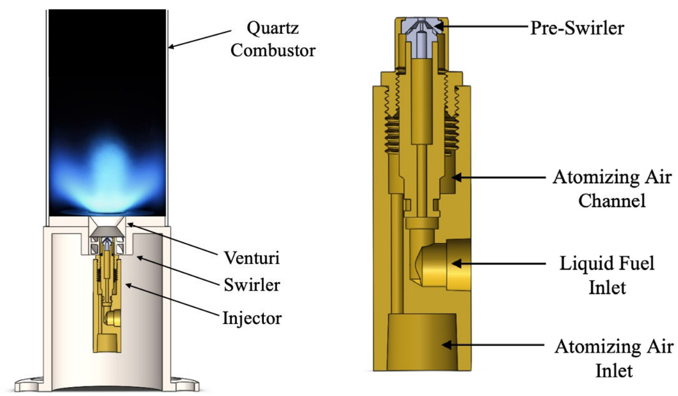
Clean Wood Combustion

Fuel Flexible Liquid Atomization for Clean Combustion



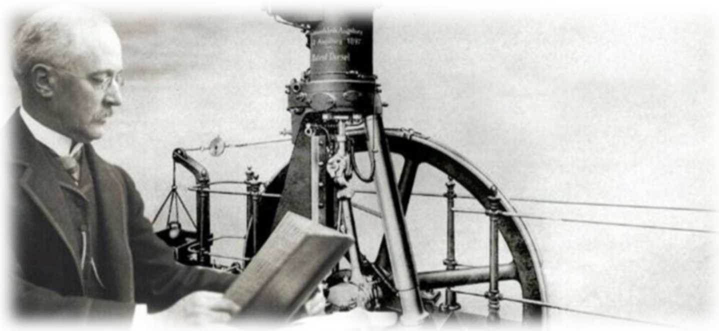


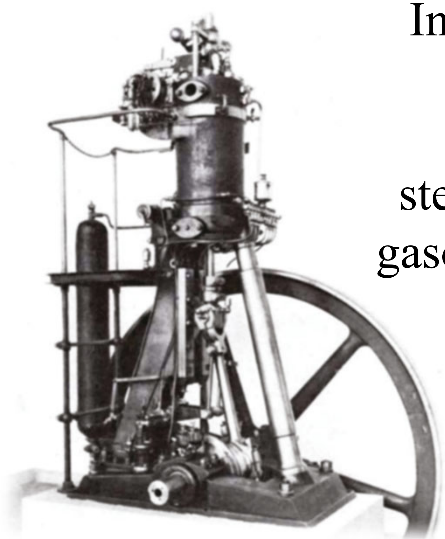
Lean Direct Injection Combustion



(a) (b)

Focus of this talk: Combustion for Diesel Engines





Introduced in 1897
26% efficiency
better than
steam engine (<7%)
gasoline engine (17%)

Soot → Insufficient Oxidation

NOx → High Flame Temperature

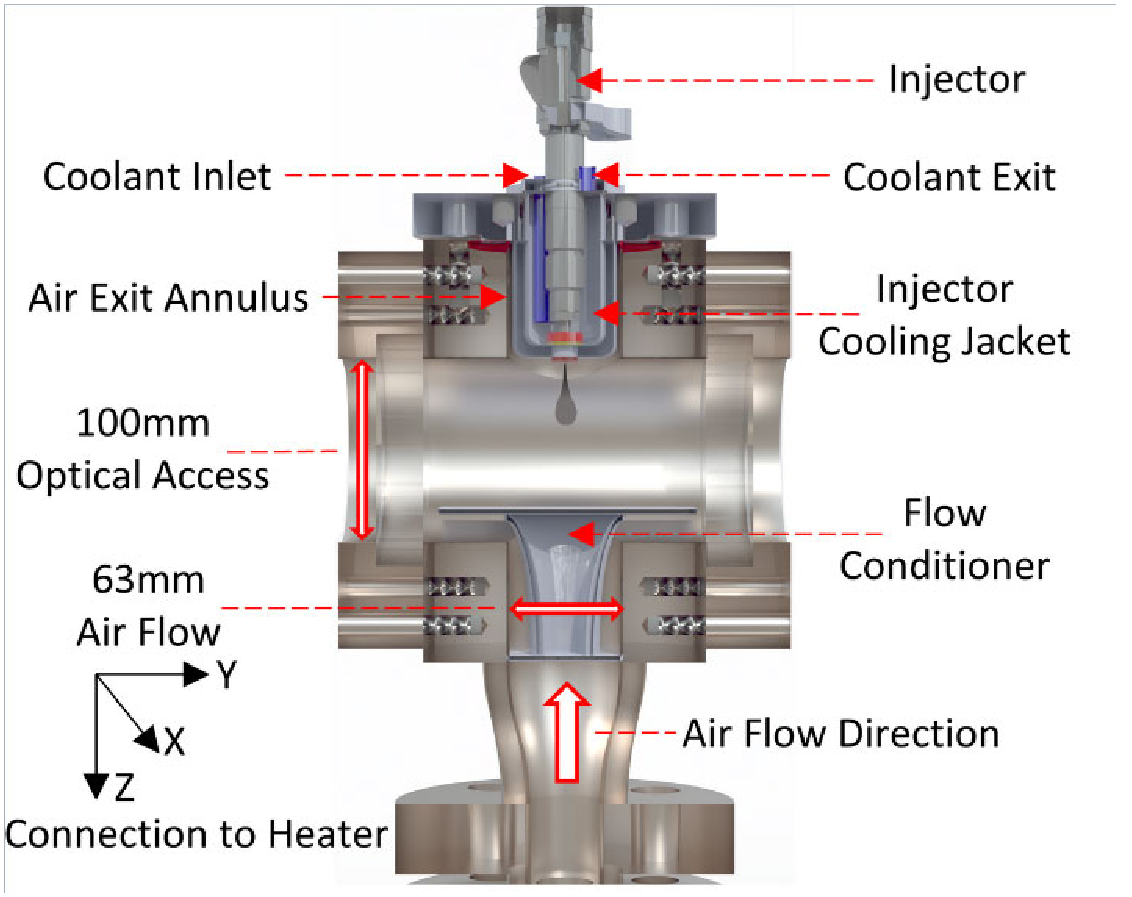
CO → Incomplete Combustion

UHC → Incomplete Combustion

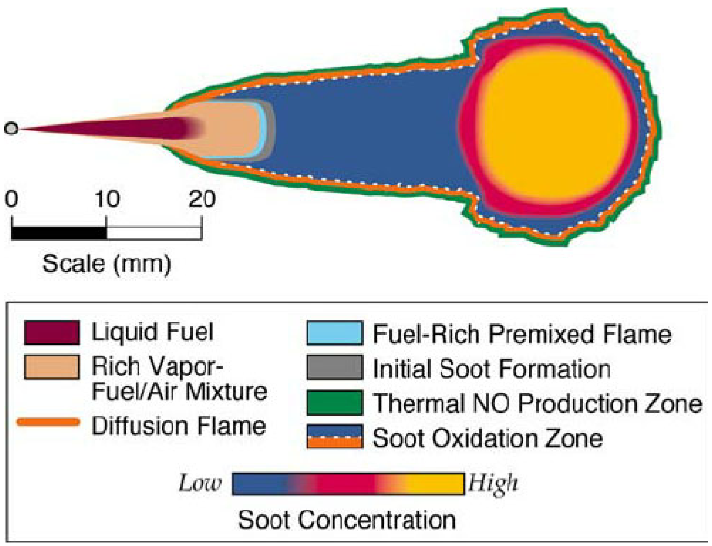
Incomplete Combustion & Post-Injection Dribble

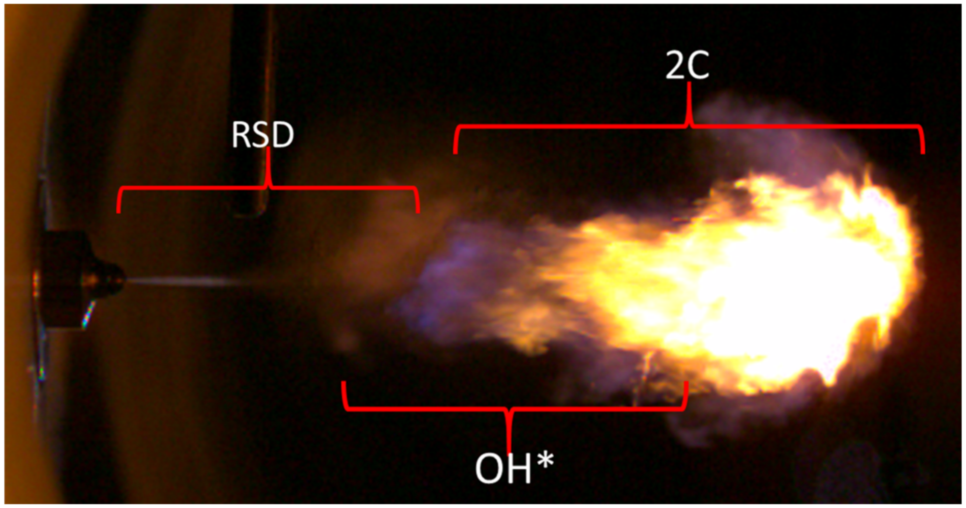
High Pressure Spray Combustion Facility

- Many existing facilities utilize a constant volume test chamber
- A pre-combustion process in BATCH mode is used to attain high-pressure, high-temperature ambient conditions of the experiment
- We built a contact pressure test chamber with a continuous flow of compressed preheated air
- Experiments with ambient air at up to 60 bar and 1000 C can be performed in quick succession, up 8 injections per minute to acquire statistically significant data set of fuel injections



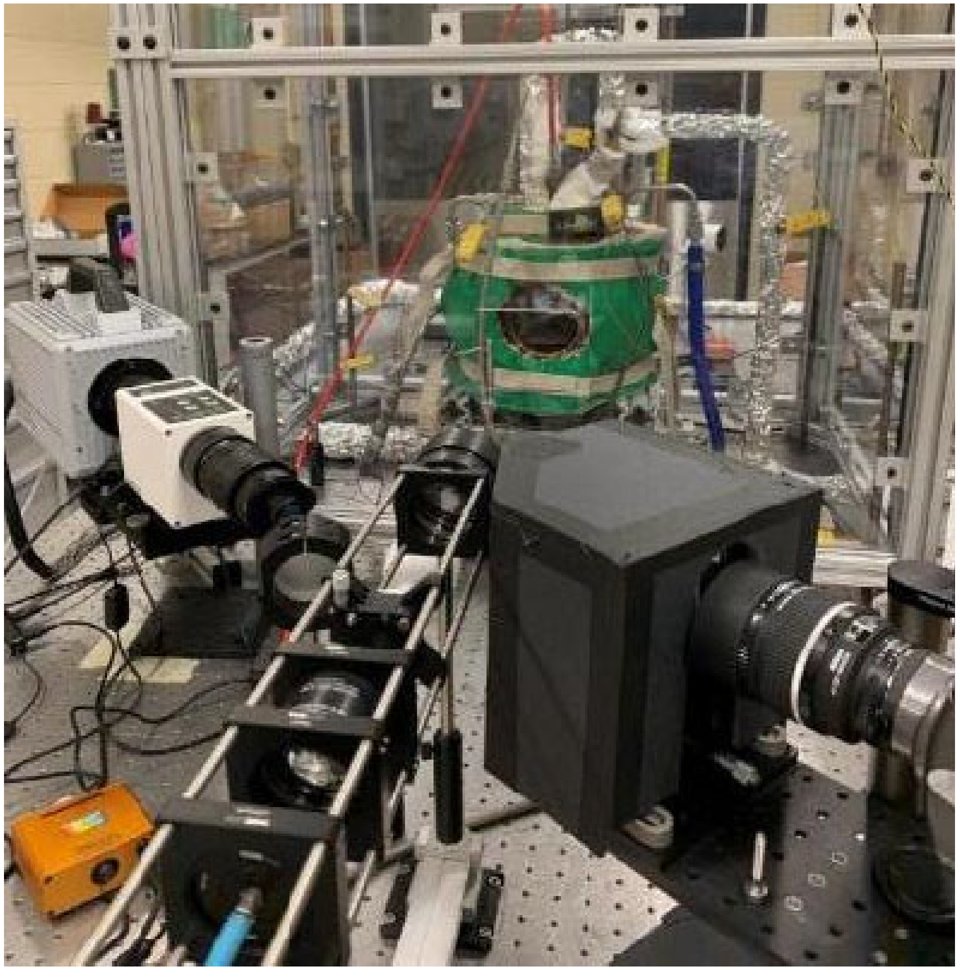
First View

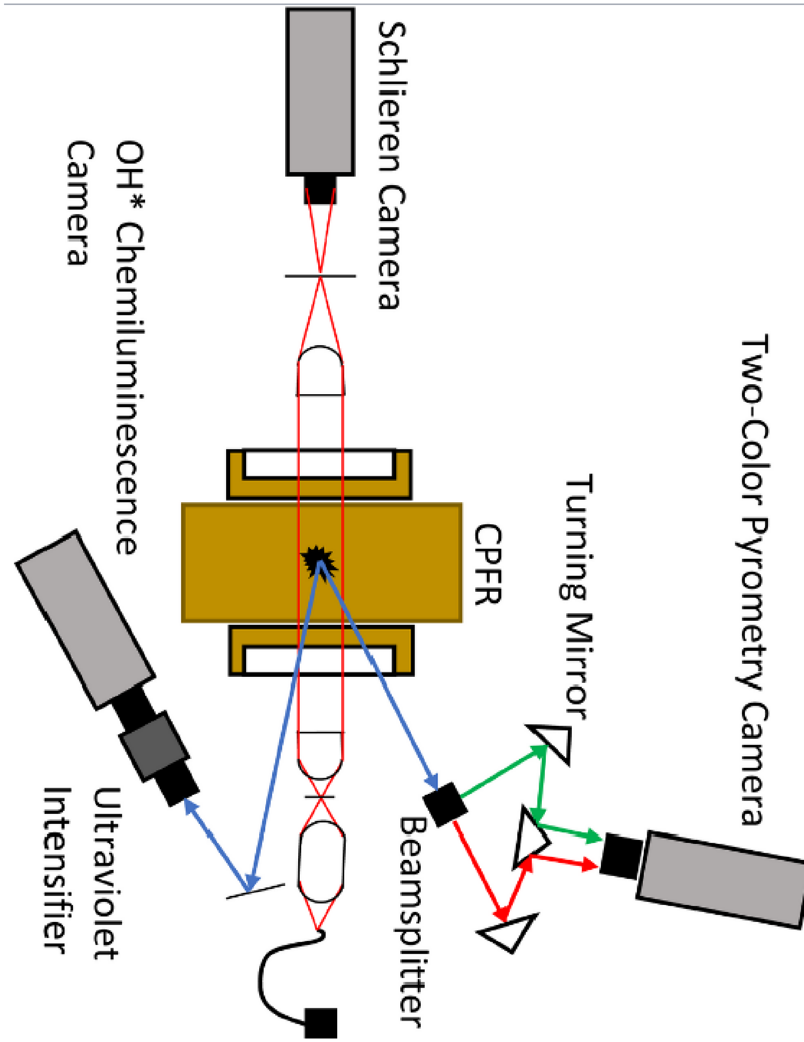




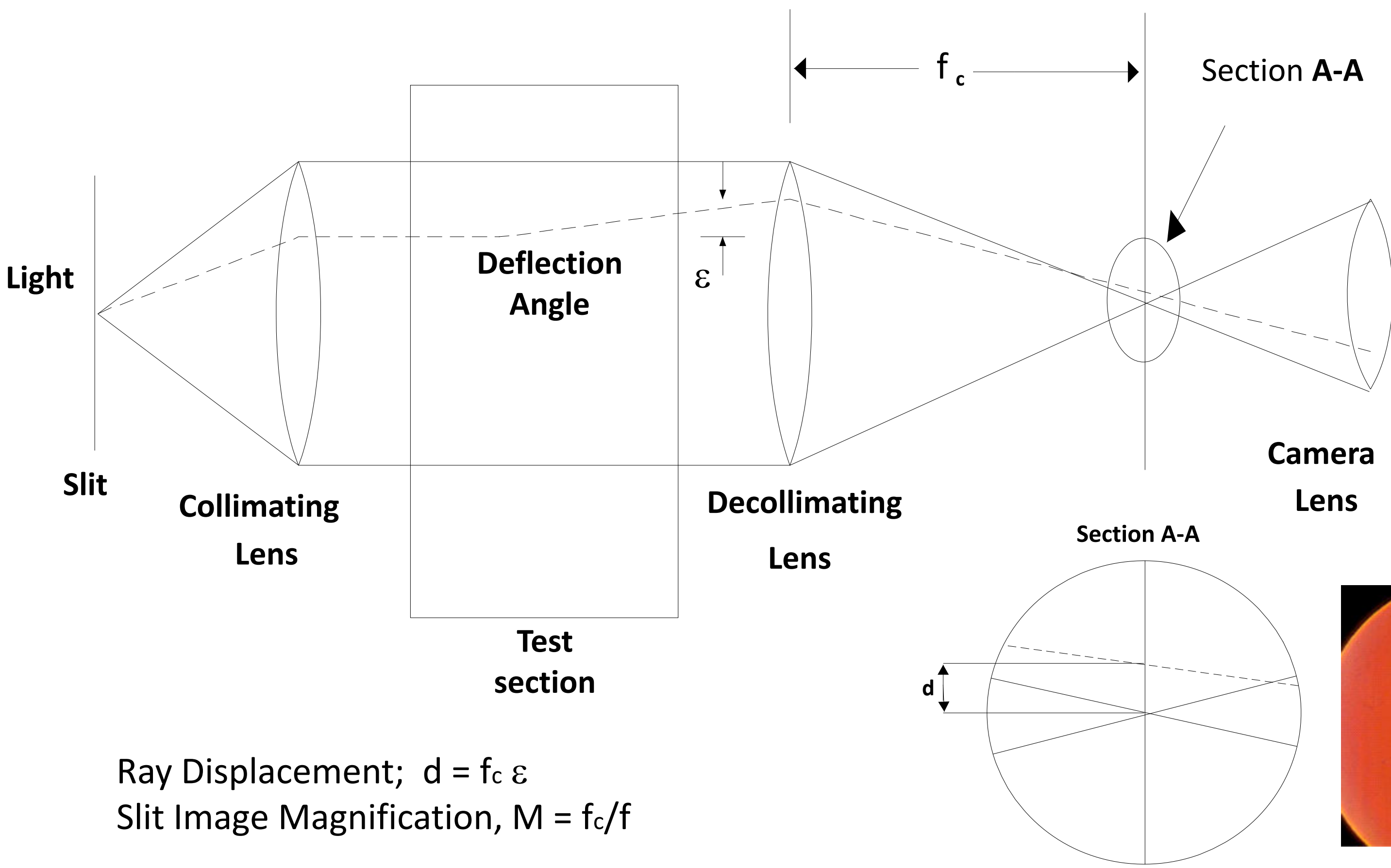
Engine out soot depends upon the Lift-off Length or axial distance where flame stabilizes.

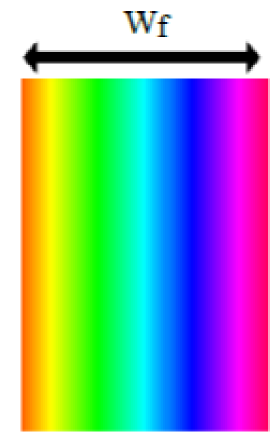
High-Speed Spray Diagnostics

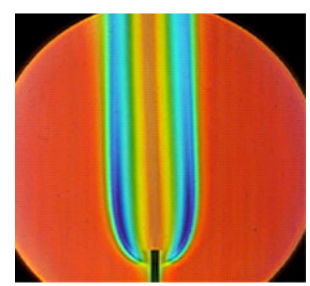


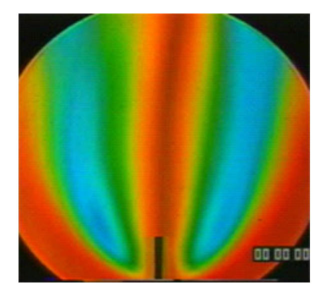


Rainbow Schlieren Deflectometry (RSD)





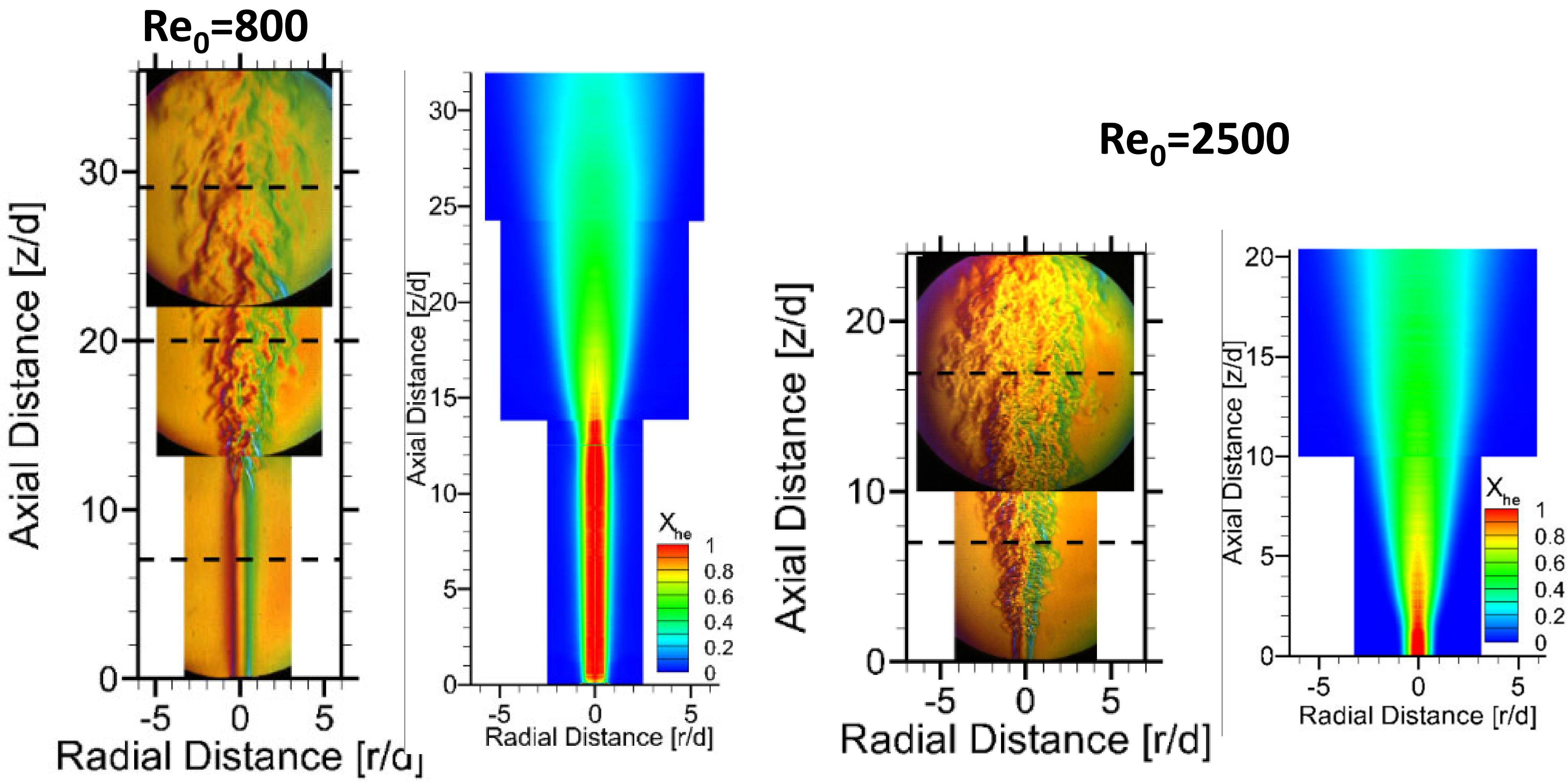




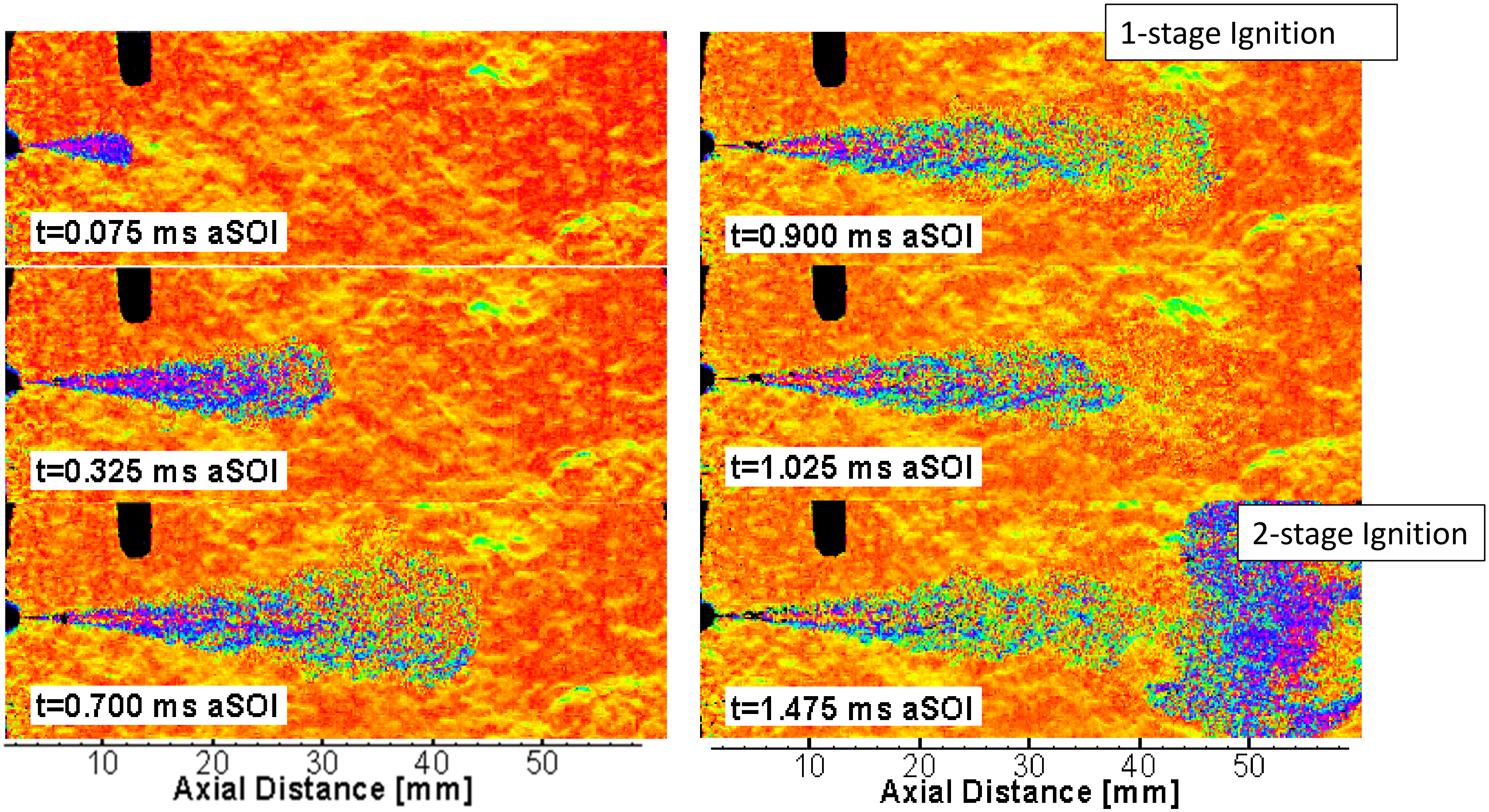
Ray Displacement; $d = f_c\, \varepsilon$

Slit Image Magnification, $M = f_c/f$

RSD Images and Local Mole Fraction Contours in Turbulent Helium Jet



Rainbow Schlieren Images



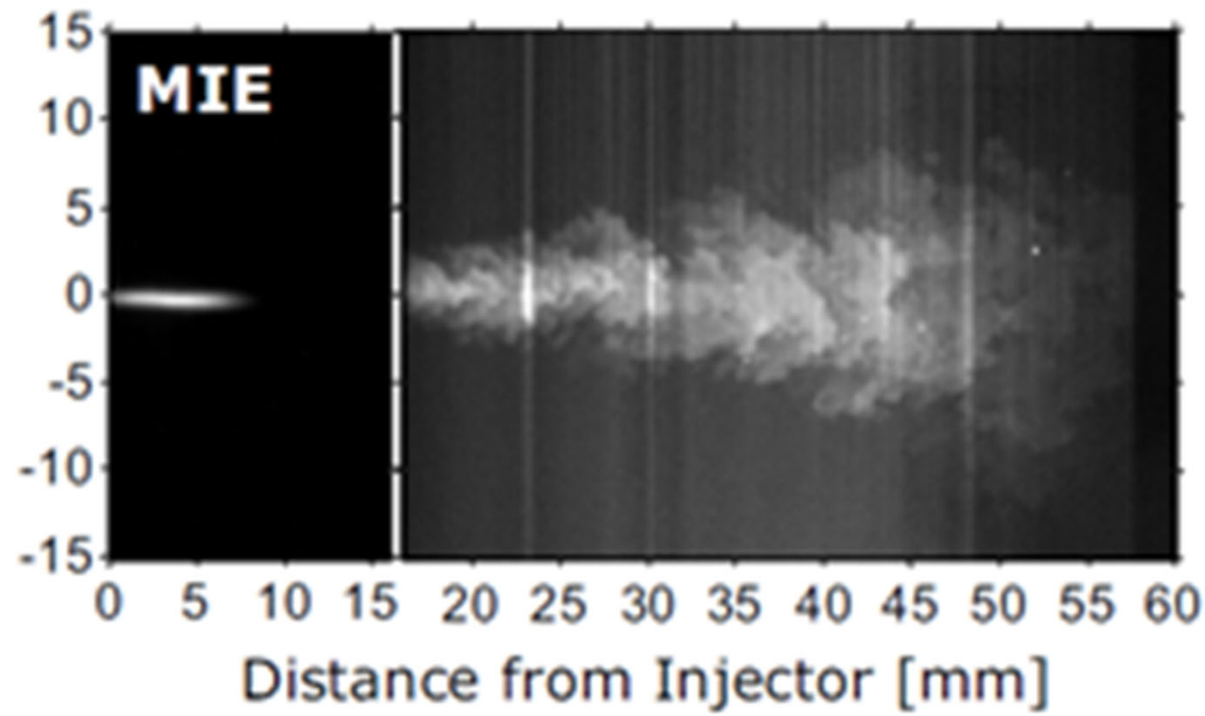
Liquid Length and Vapor Length

Requires multiple diagnostics

Liquid regime
- Mie scattering
- Diffuse background imaging (DBI)

Vapor regime
- Schlieren
- Shadowgraphy
- Rayleigh scattering

Idicheria et al (2007)

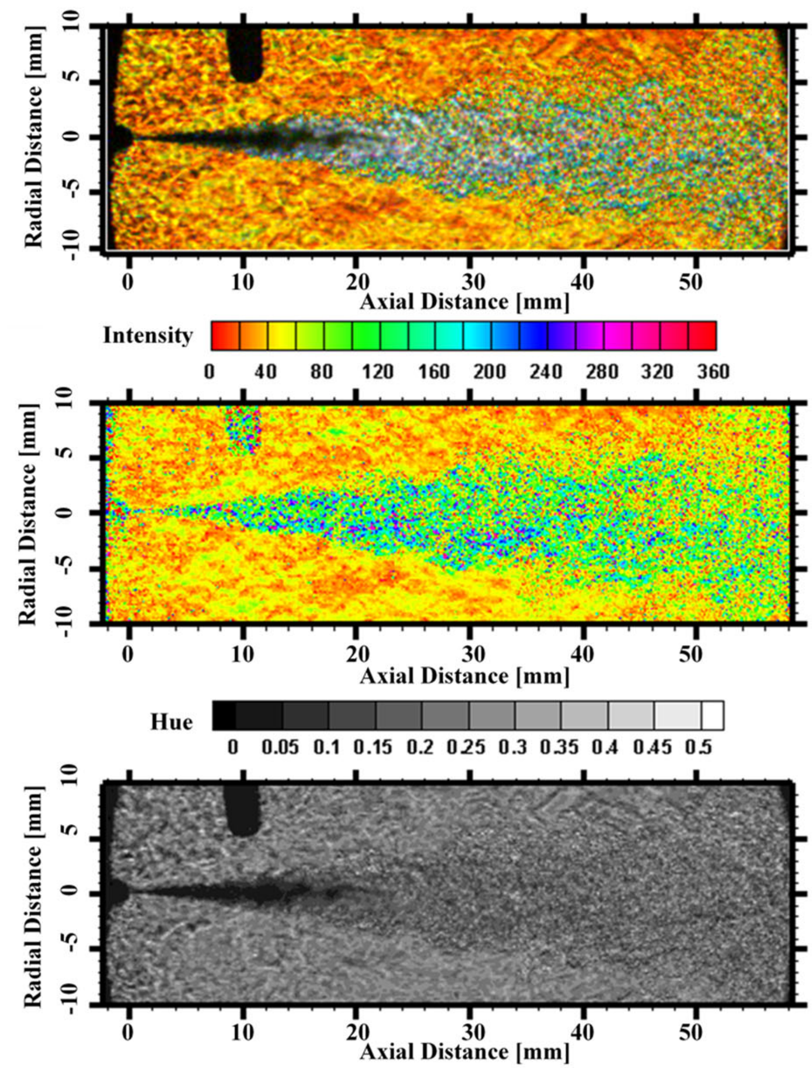


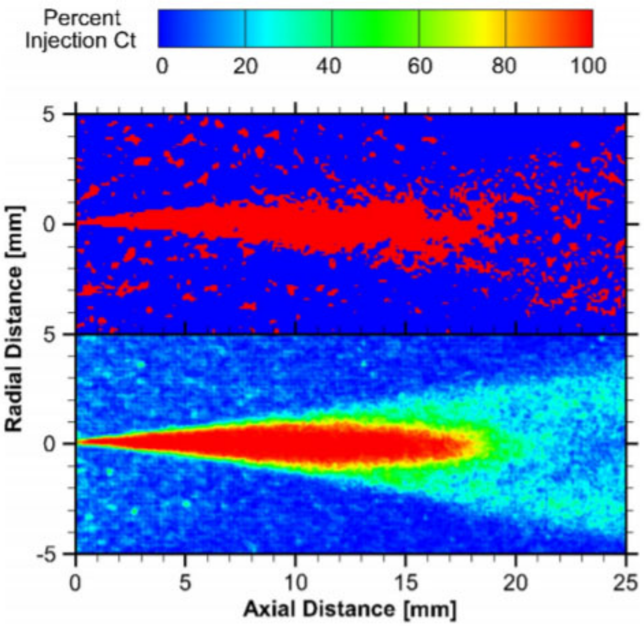
RSD Image Analysis – Two signals in one image

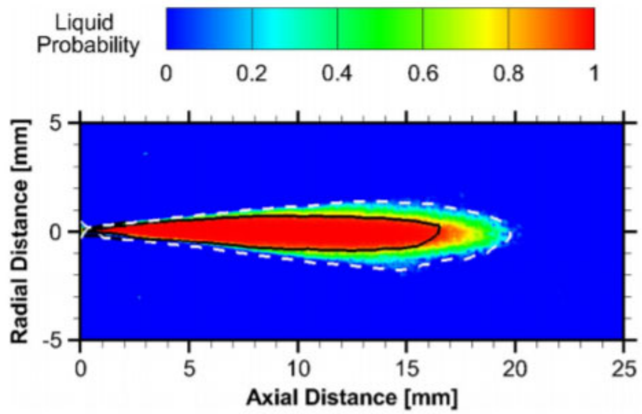
- RSD Image (top)

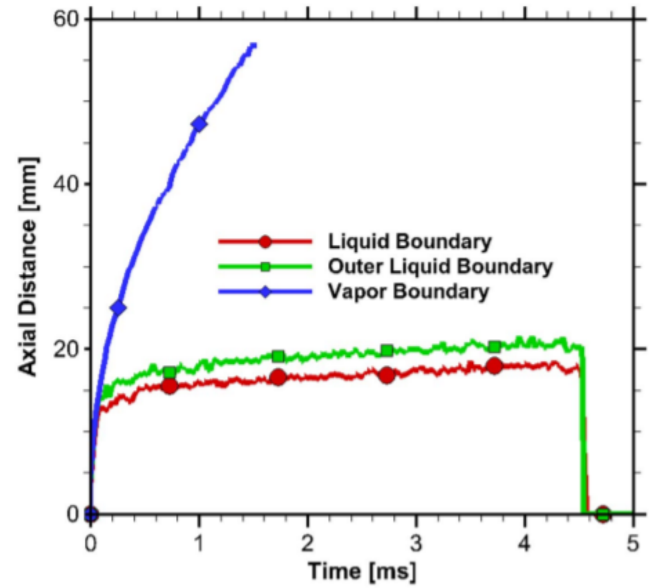
 - Hue to quantify vapor zone (middle)

 - Intensity (similar to shadowgraph) to quantify liquid zne (bottom)









Liquid boundary detection
Vapor boundary detection

Good agreement with published data

Table 2. Comparison of Liquid Boundary, Outer Liquid Boundary and Siebers' Model for the Two *n*-Heptane Cases

Case	Liquid Length (mm)	Outer Liquid Length (mm)	Siebers' Model (mm)
1	17.3 ± 1.1	20.0 ± 1.2	20.2
2	9.0 ± 0.7	10.3 ± 1.0	10.8

Summary Remarks

- RSD provides greater insight compared to conventional schlieren, and yet it is simple to implement. Recommend community to use RSD more regularly.
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- Despite being line-of-sight, 2CP can provide useful information about soot, at least for qualitative comparisons. Recommend users to implement the novel 2CP setup discussed here.
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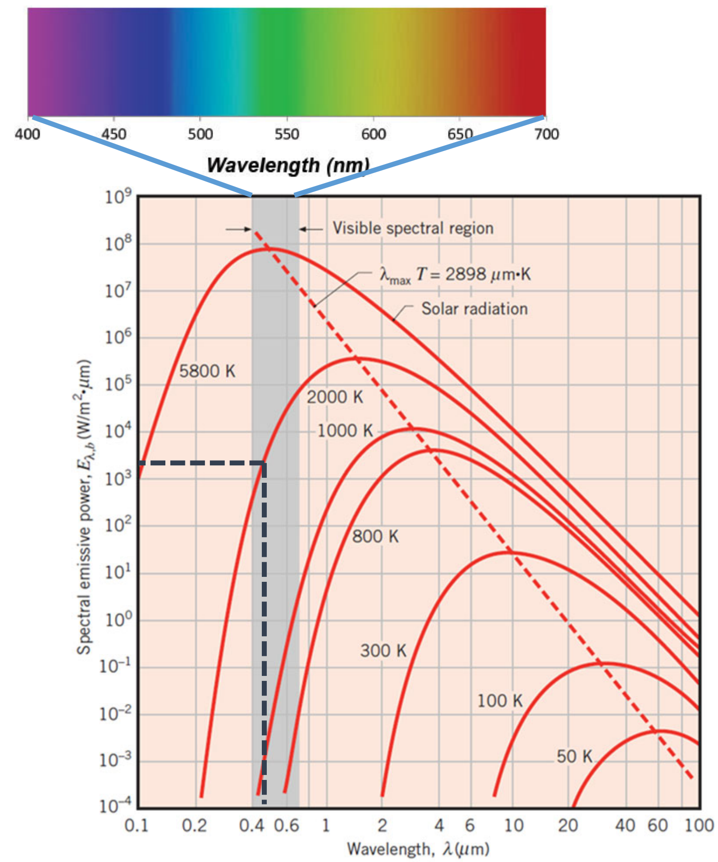
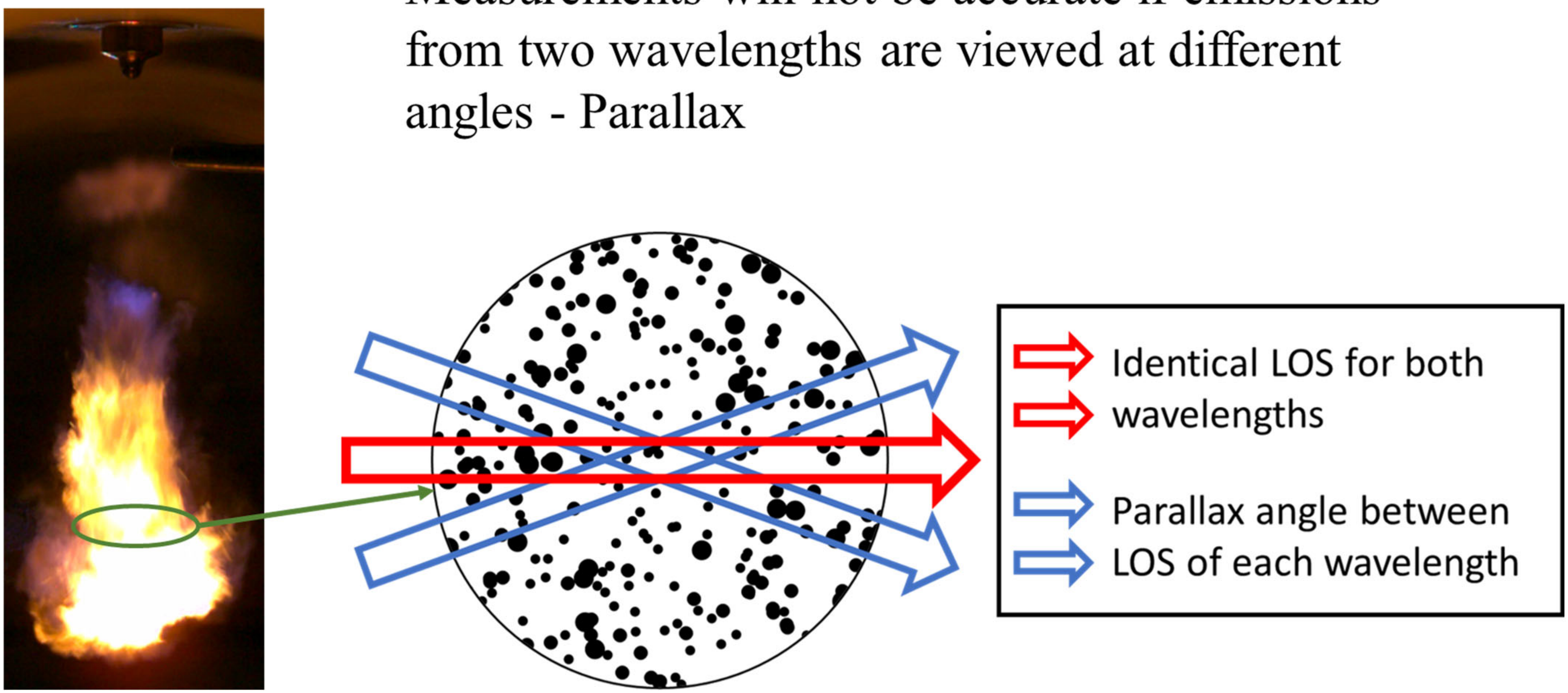
Two-Color Pyrometry (2CP)

- 2CP is a line-of-site technique to measure soot temperature and soot concentration
- Soot particles radiate visible light
- Radiative emission can be related to soot temperature
- Radiative emission data at two distinct wavelengths are necessary to resolve the emissivity
- Wavelengths of 550 nm and 650 nm are used to avoid specific band emissions from radical species



[8]

- Measurements will not be accurate if emissions from two wavelengths are viewed at different angles - Parallax



2CP Equations at a Pixel Location

- Planck's Law:

$$E_{b,\lambda} = \frac{C_1}{\lambda^5 [e^{\left(C_2/\lambda T\right)} - 1]}$$ ***Eq. (1)***

- Emissive power for a non-blackbody:

$$E_\lambda(T) = \epsilon_\lambda E_{b,\lambda}(T) = E_{b,\lambda}(T_a)$$ ***Eq. (2)***

- Empirical Emissivity-Soot relationship :

$$\epsilon_\lambda = 1 - e^{-KL/\lambda^\alpha}$$ ***Eq. (3)***

- Combining:

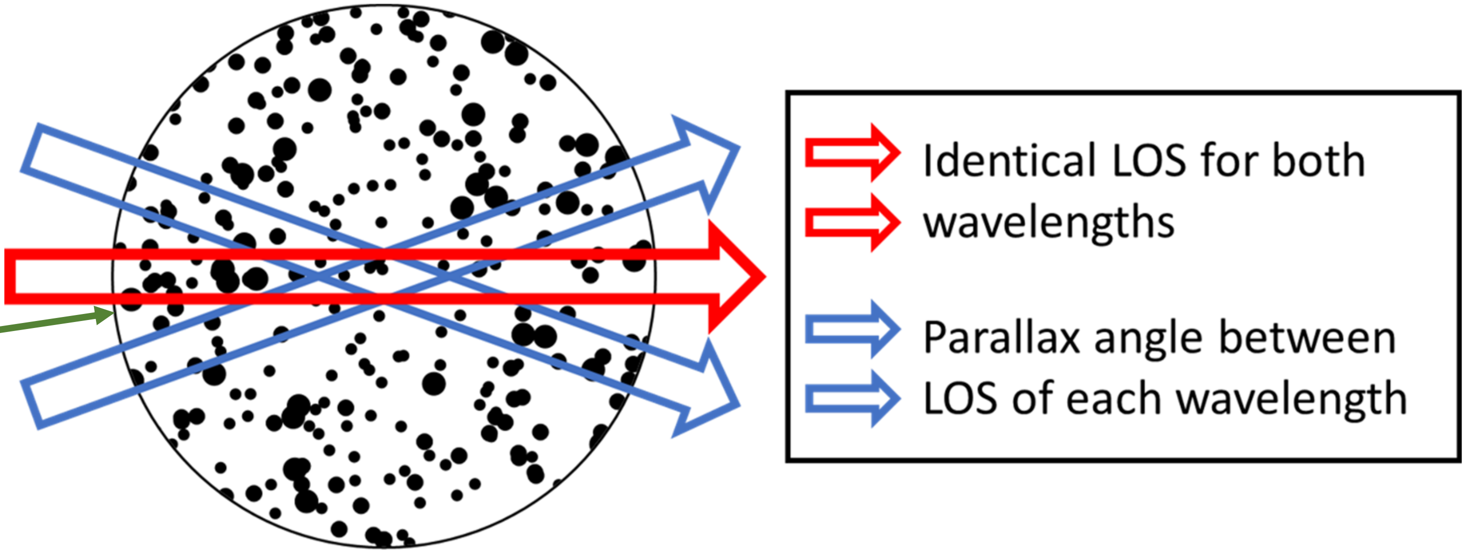
$$KL = \left[1 - \left(\frac{e^{(C_2/\lambda_1 T)} - 1}{e^{(C_2/\lambda_1 T_{a_1})} - 1}\right)\right]^{{\lambda_1}^\alpha} = \left[1 - \left(\frac{e^{(C_2/\lambda_2 T)} - 1}{e^{(C_2/\lambda_2 T_{a_2})} - 1}\right)\right]^{{\lambda_2}^\alpha}$$ ***Eq. (4)***

- Soot Mass:

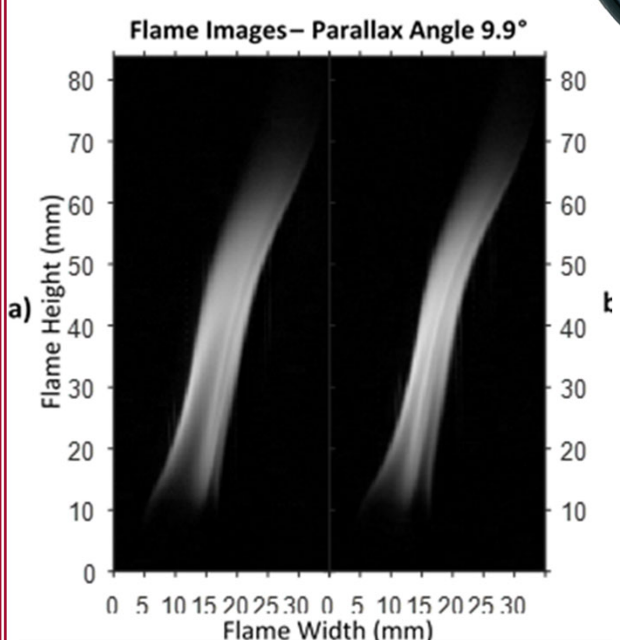
$$m_s = \Delta a_{px} \frac{\rho_p}{6\pi E(m)} \sum KL$$ ***Eq. (5)***

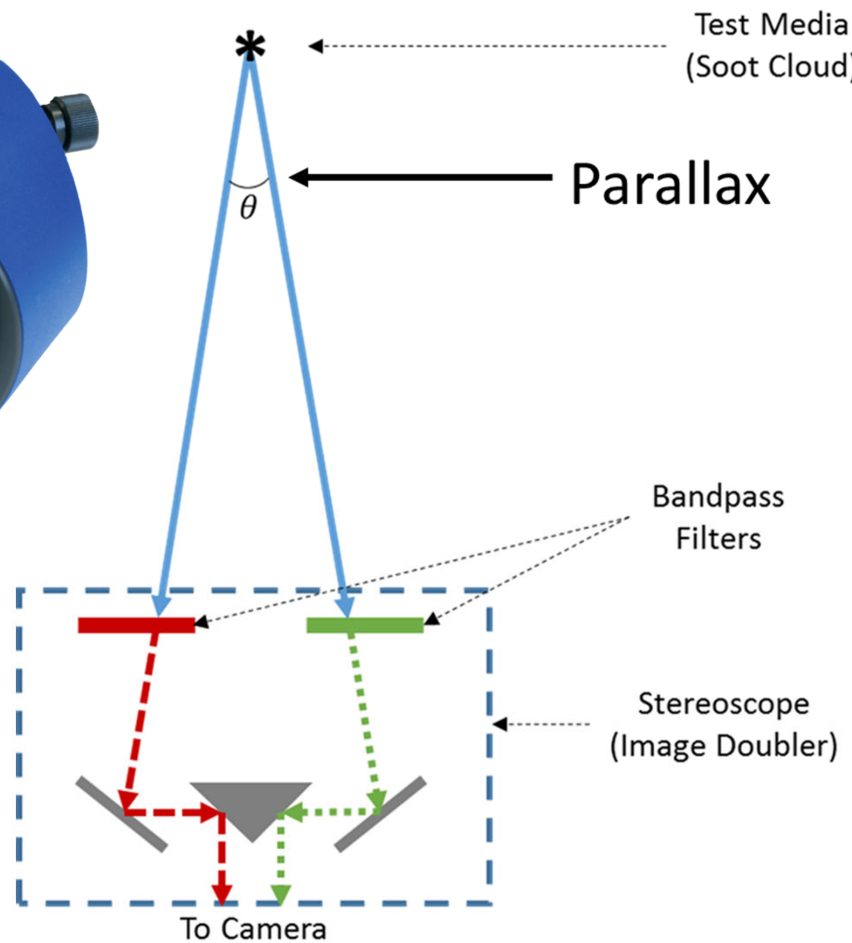
Importance of View Angles

- Measurements will not be accurate if emissions from two wavelengths are viewed at different angles - Parallax

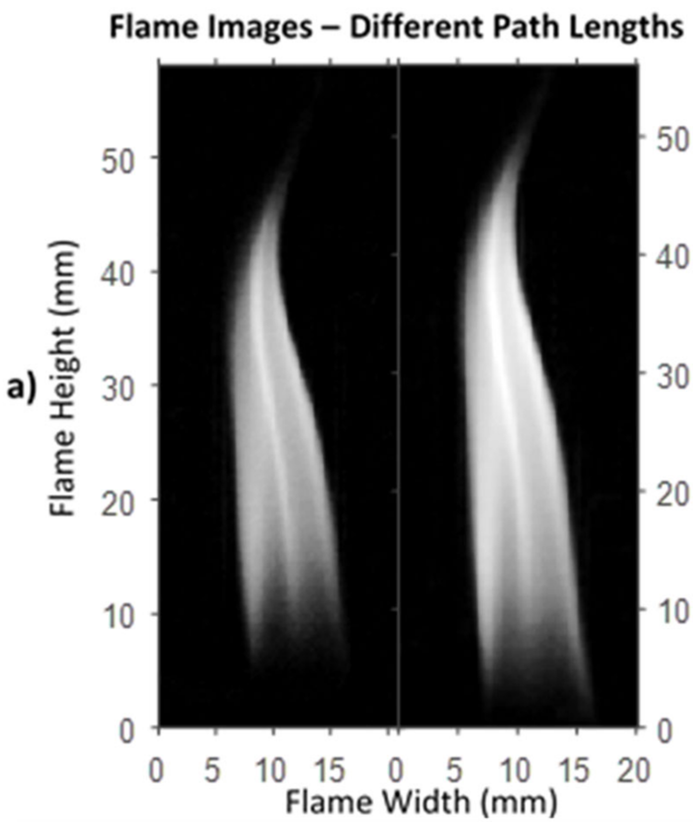


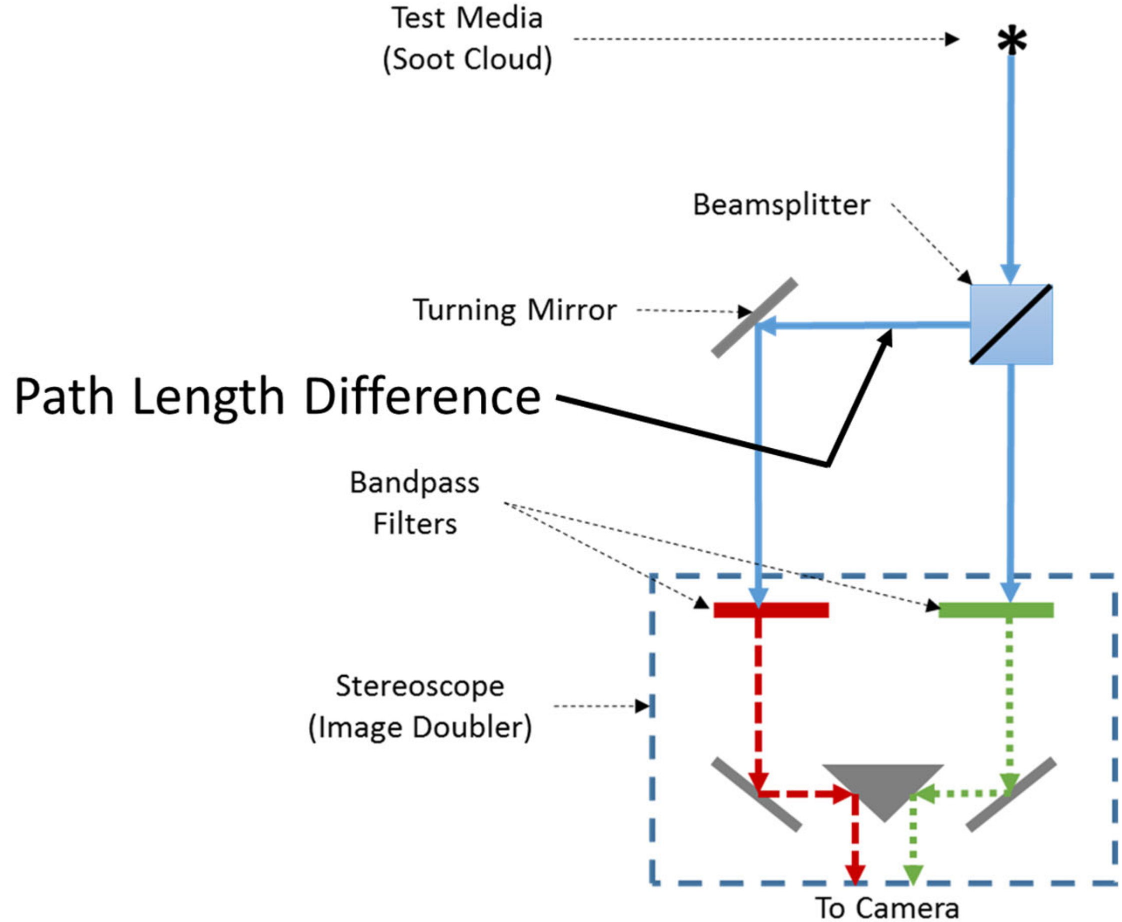
Multiple Cameras or Image Doubler cause Parallax





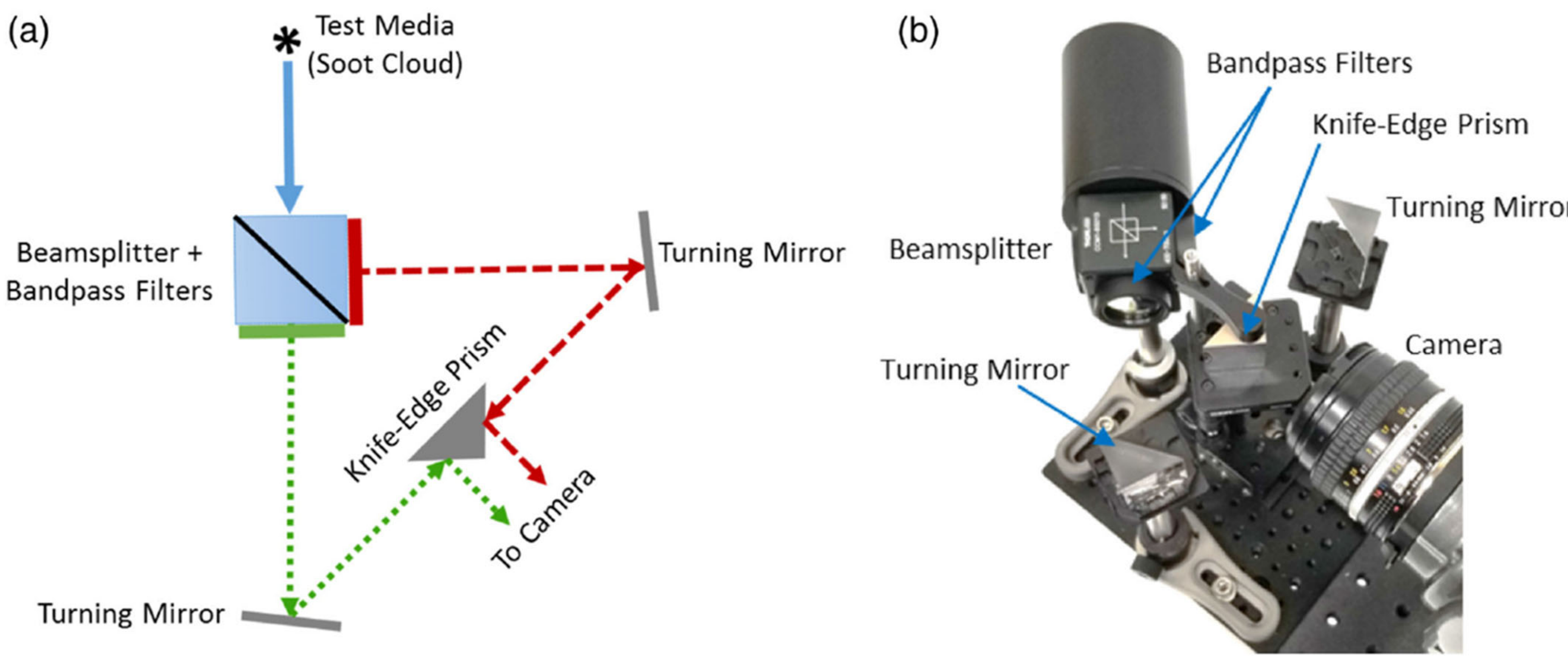
Beam splitter solves parallax but introduces path length error



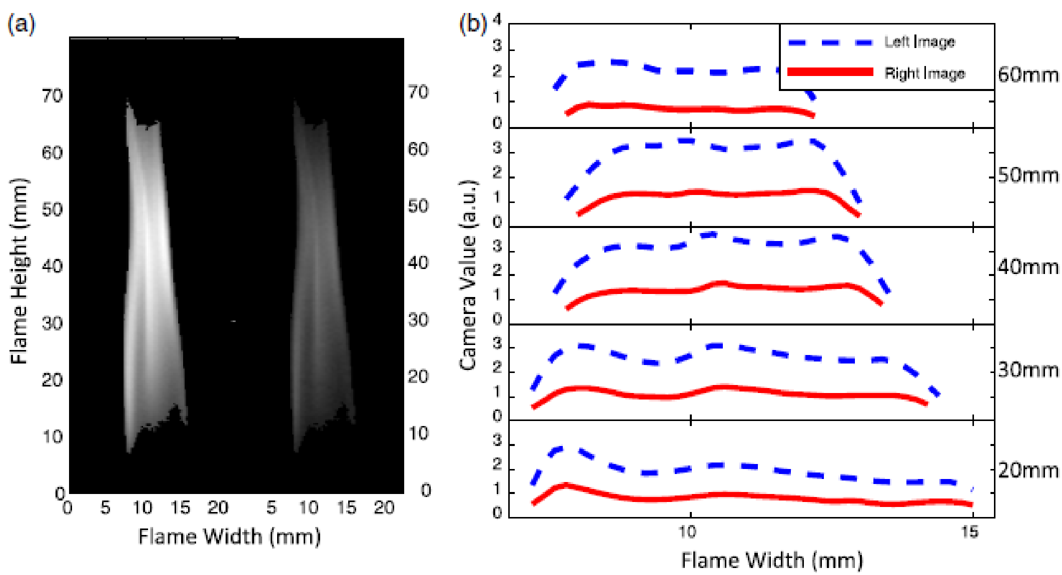


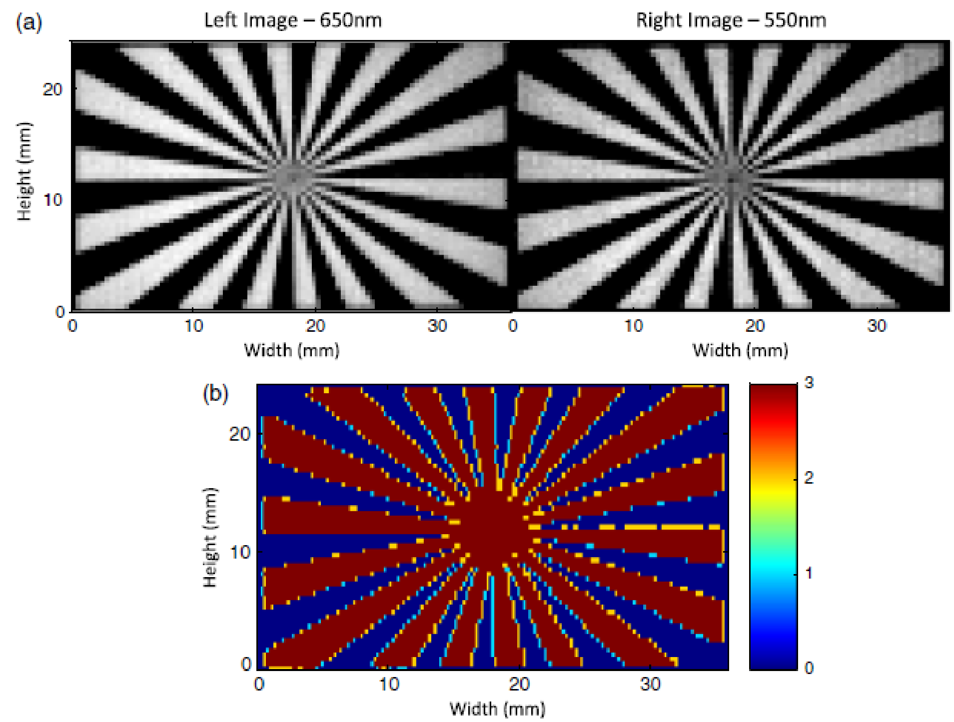
A Novel Optical Setup

- No parallax effect and equal path lengths



Accurate Pixel Mapping with New Design





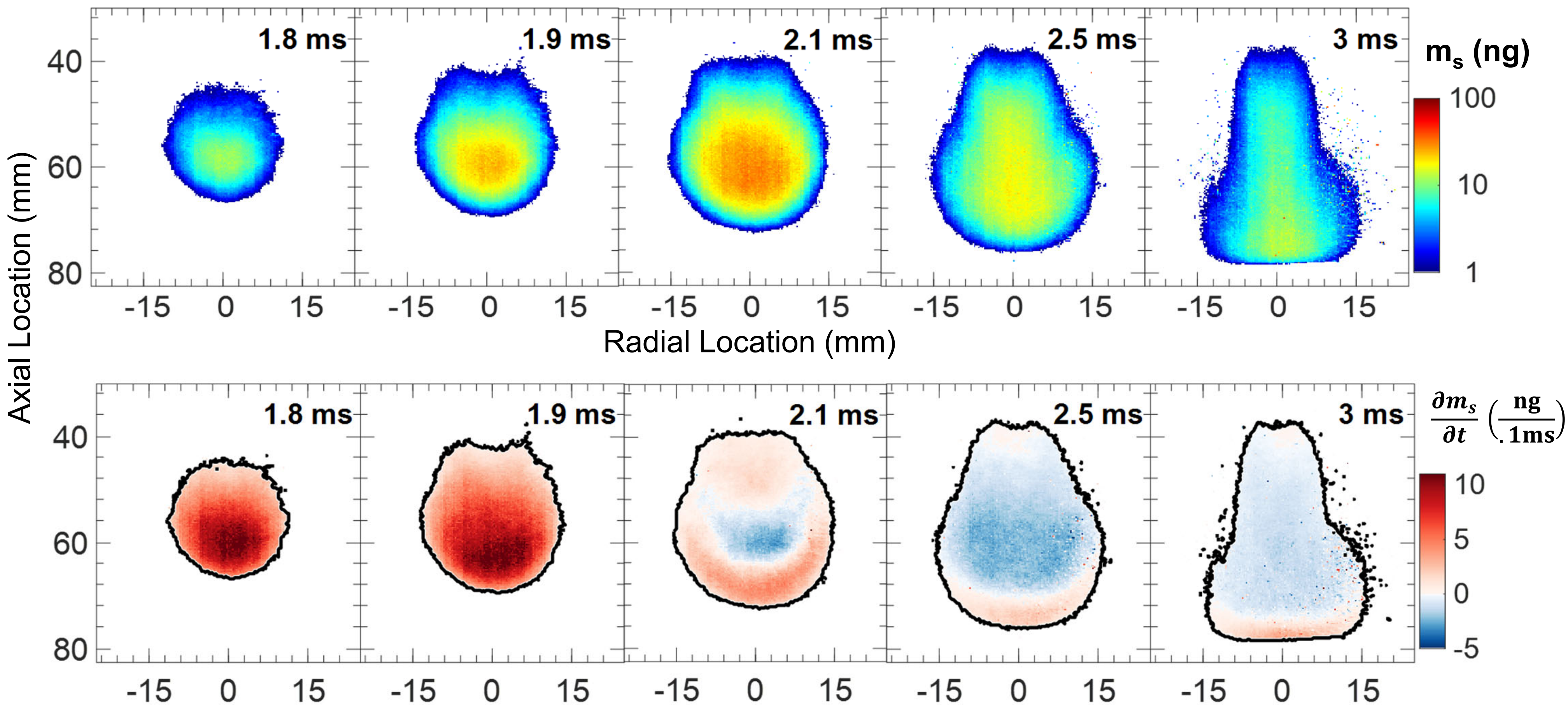
0 – Matching Dark Pixels
1 or 2 – Mismatched Light/Dark Pixels
3 – Matching Light Pixels

Experiment Conditions

- Actual ambient air and fuel injection conditions for **500 repeated fuel injection experiments**
- Variation is indicated by 95% confidence interval of the mean

Property	Units	Value
Ambient Air		
Temperature	$[K]$	807 $\pm$4
Pressure	$[MPa]$	3.0 $\pm$0.02
Density	$[kg/m^3]$	13.0 $\pm$ 0.2
Fuel and Injector		
Type		n-heptane
Temperature	$[K]$	358 $\pm$0.2
Pressure	$[MPa]$	98.9 $\pm$0.8
Injector Orifice Size	$[\mu m)]$	104
Injection Duration	$[ms]$	4.5

Soot Mass and Soot Mass Rate of Change



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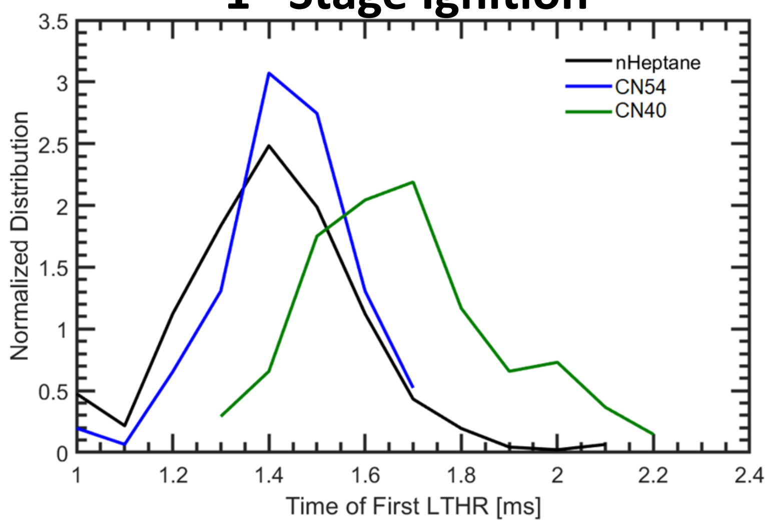
Physical versus chemical properties

Tested Fuels

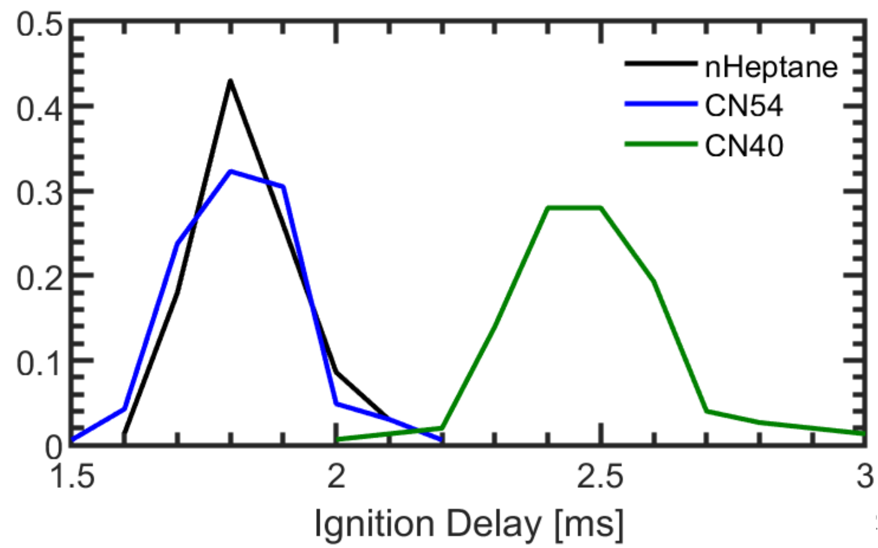
	n-heptane	CN54	CN40
CN	53.8	53.8	40
Heat to Vap. [kJ/kg]	399	634	589

- Ignition delay has well-defined statistical distribution with injections
- N-heptane and CN54 have similar distributions as expected
- CN40 has longer ignition delay (1st stage and 2nd stage) as expected

1st Stage Ignition



Main Ignition

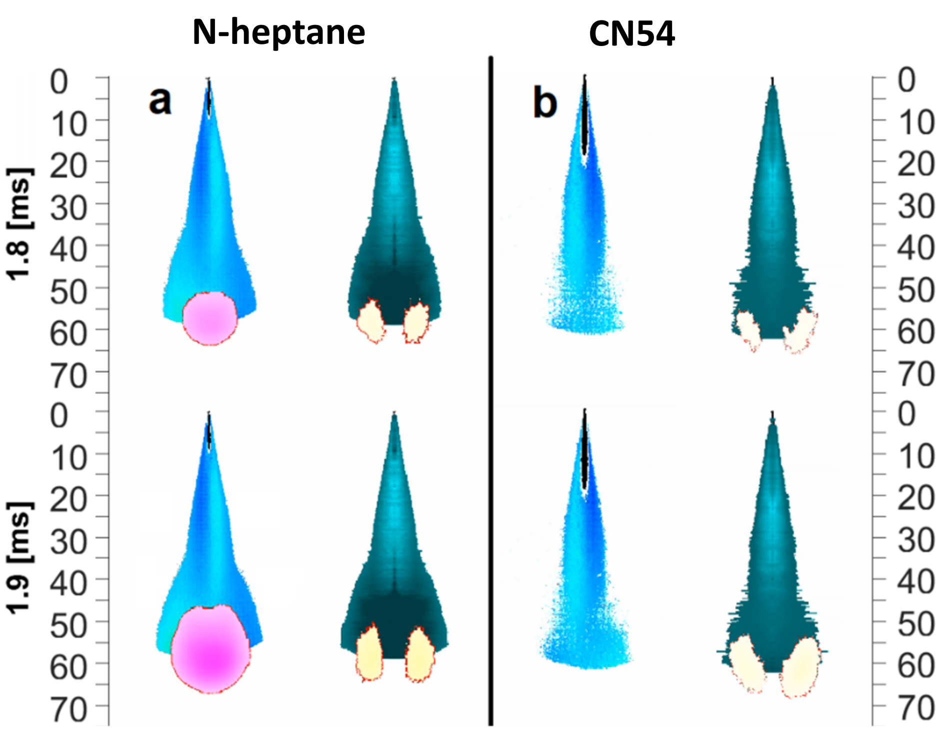


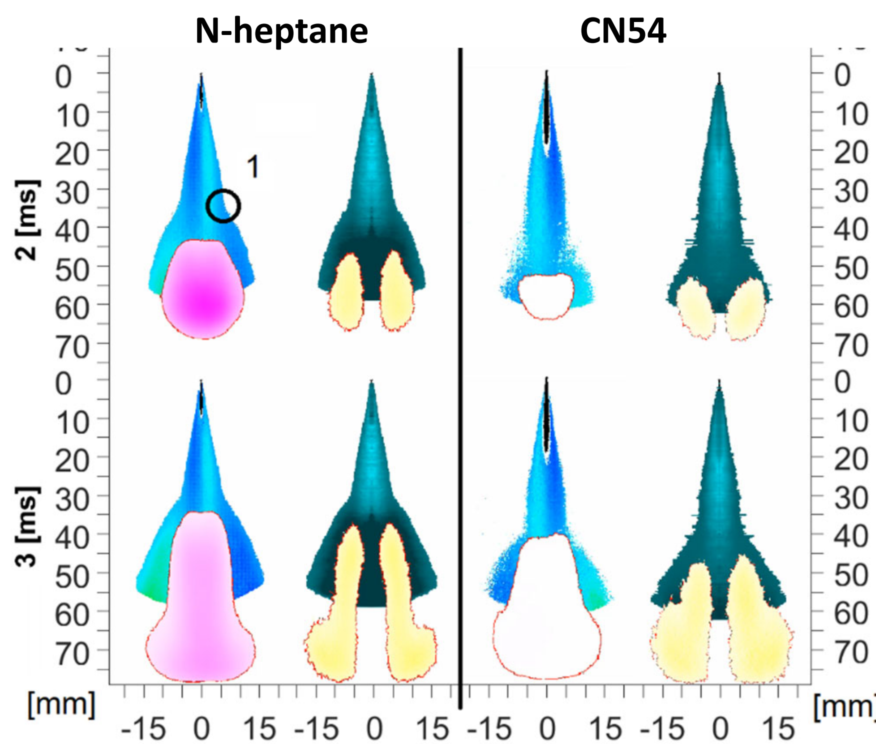
Composite Images

Lift column : RSD image superimposed with soot mass

Right column: Refractive index superimposed with OH* chemiluminescence

- Why CN54 flame has longer lift-off length and much less soot compared to N-heptane flame





Role of Liquid Length, physical properties

- Ignition location is different for three fuels, shorter for N-heptane
- N-heptane liftoff length is shorter
- CN54 lift-off length is longer
- CN40 lift-off length is longer
- These differences are related to liquid length which depends on the heat to vaporize the fuel

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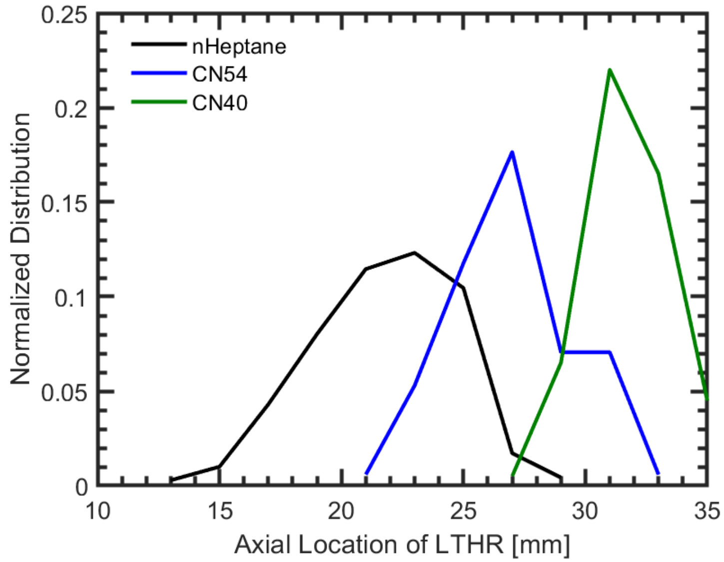

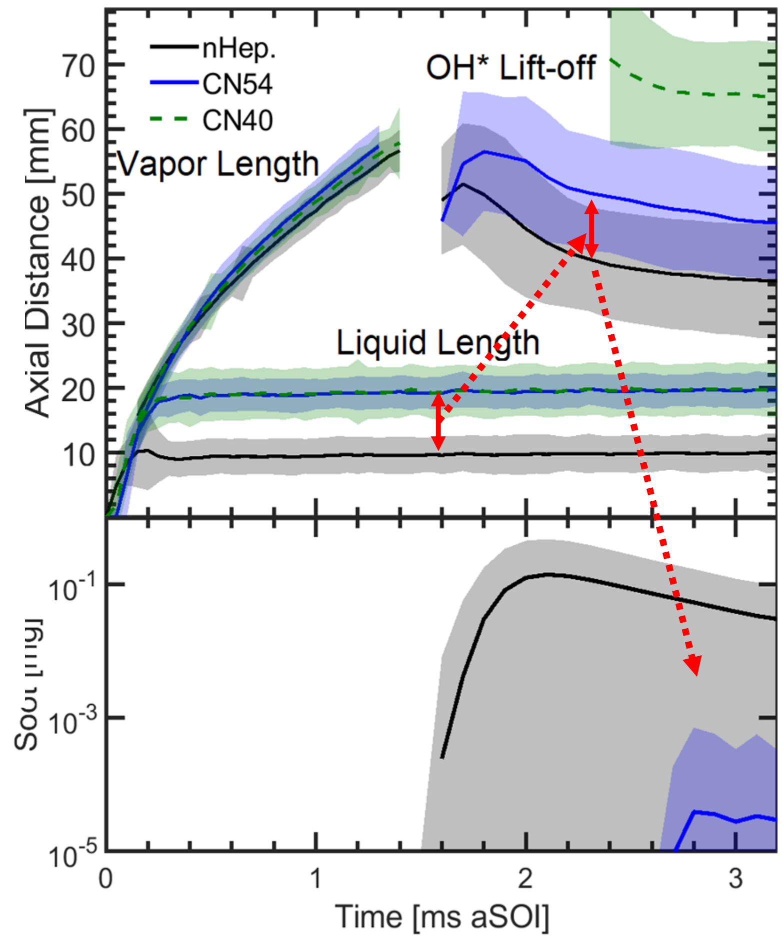

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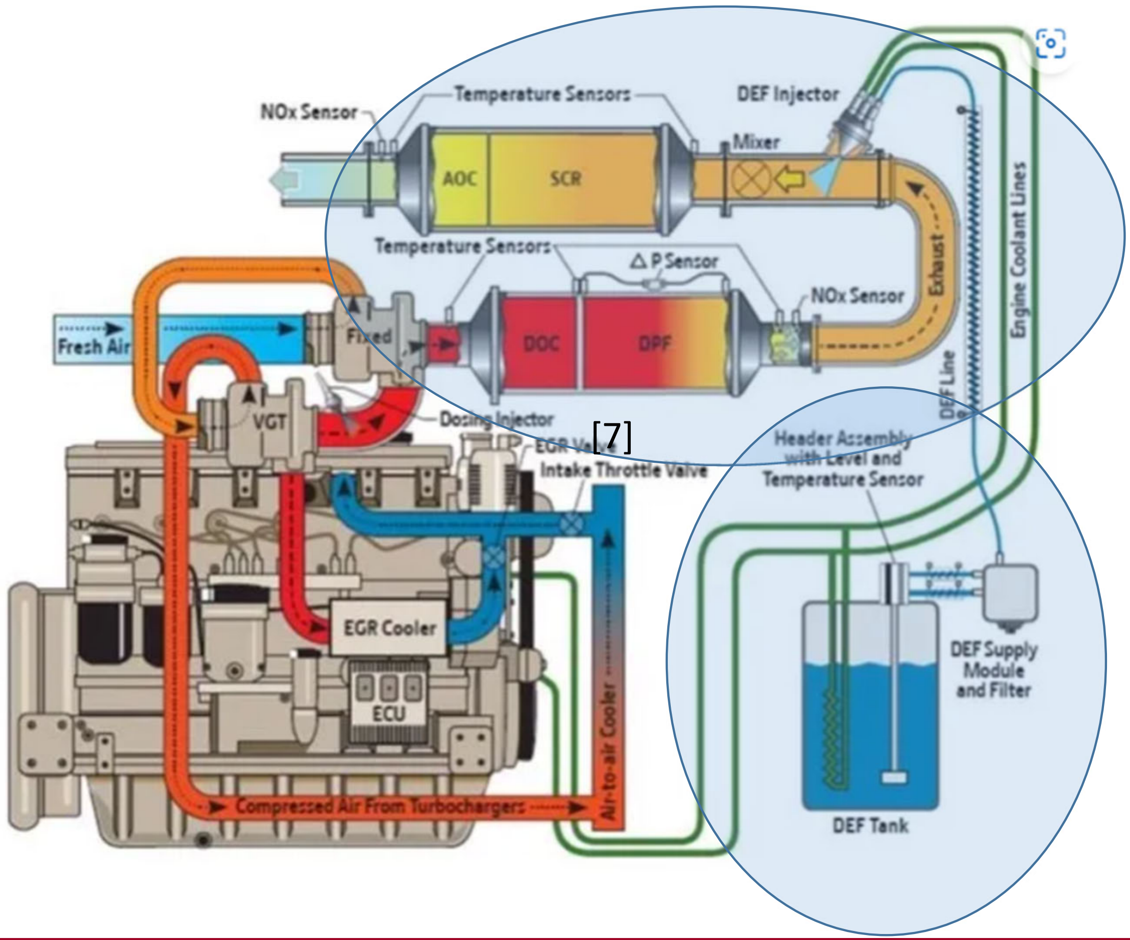
Acknowledgements

- DE-EE-0007301, Development and Validation of Physics-Based Sub-models of High-Pressure Supercritical Fuel Injection at Diesel Conditions, US Department of Energy, Jan 1, 2016-August 31, 2020.

- DE-EE0007980, Characterization of Biomass-Based Fuels and Fuel Blends for Low-Emissions, Advanced Compression Ignition Engines, US Department of Energy, Feb 1, 2017 – January 31, 2022.

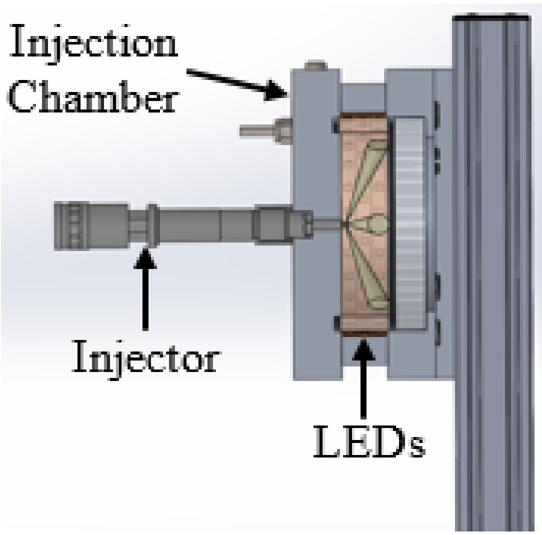
- DE-EE0008483, Bioproduction and Evaluation of Renewable Butyl Acetate as a Desirable Bio-blend stock for Diesel Fuel, Department of Energy with Auburn University as the lead, July 1, 2019-December 31, 2023.

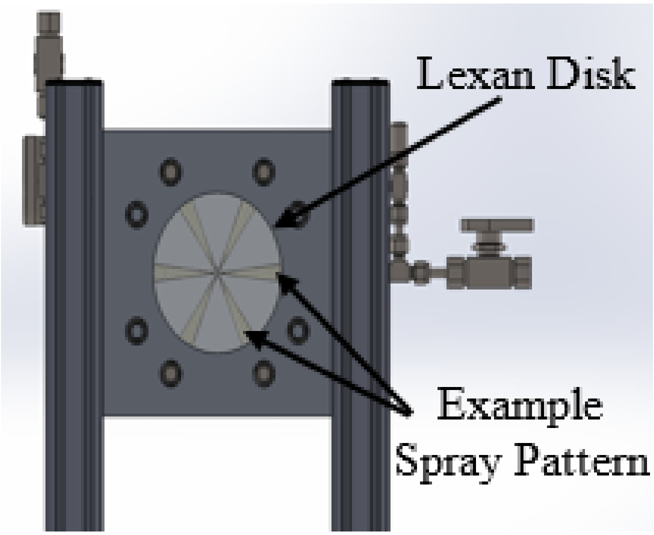
Despite combustion research, diesel engines rely increasingly on after-treatment systems to meet the emissions regulation. Significant Weight, Space, Cost.



- Diesel Oxidizing Catalyst (DOC) – CO and UHC to CO2 and H2O
- Diesel Particulate Filter (DPF) – Filters PM to acceptable levels
- Diesel Exhaust Fluid (DEF) – followed by Selective Catalytic Reduction unit (SCR) to reduce NOx to acceptable levels.

Cold Flow Optical Chamber



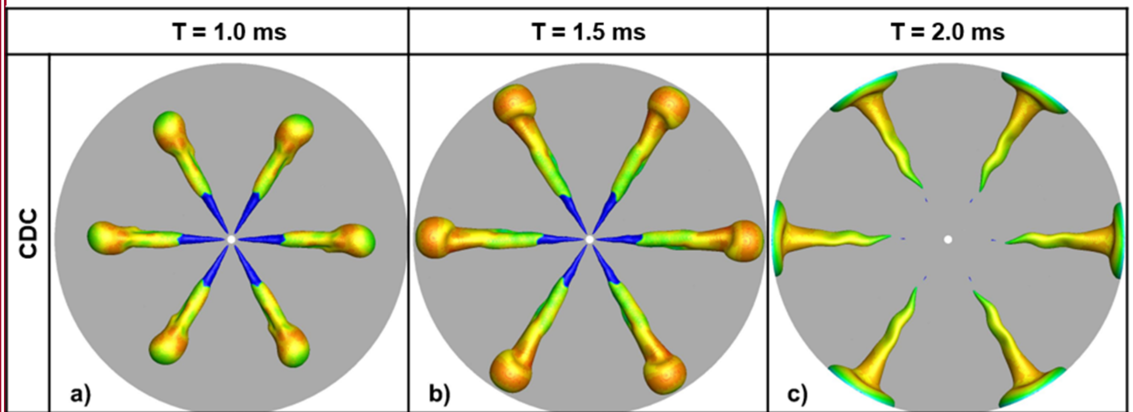


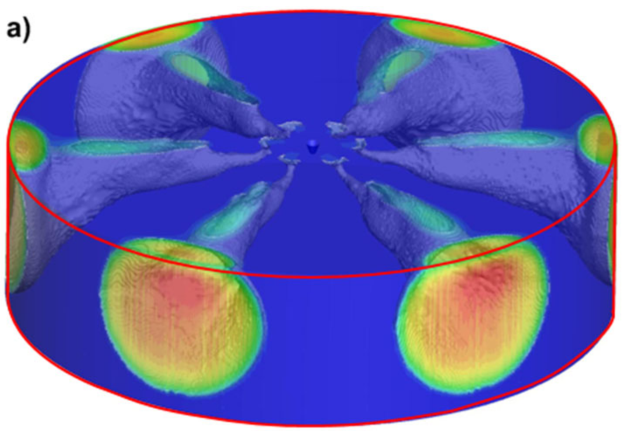
- High-speed imaging allows exploration of new concepts in a relatively simple experiment
- The chamber has a diameter of 120.7mm with a depth of 33.3 mm
- Chamber can be pressurized to achieve engine-like ambient densities
- Fuel is injected at engine realistic pressures.
- LED strips around the Lexan cylinder illuminate the chamber evenly

Conventional Diesel Combustion (CDC)

- Centrally located, multi-hole injector injects fuel almost universally in current diesel engines
- The diffusion flame impinges on the wall requiring cooling and thus, loss in thermal efficiency
- Impingement at the wall leads to flame quenching and/or liquid wall wetting which produces soot, CO, and UHCs.
- Jets compete to access air, especially in the near field

Conventional Diesel Combustion (CDC) – CFD Results





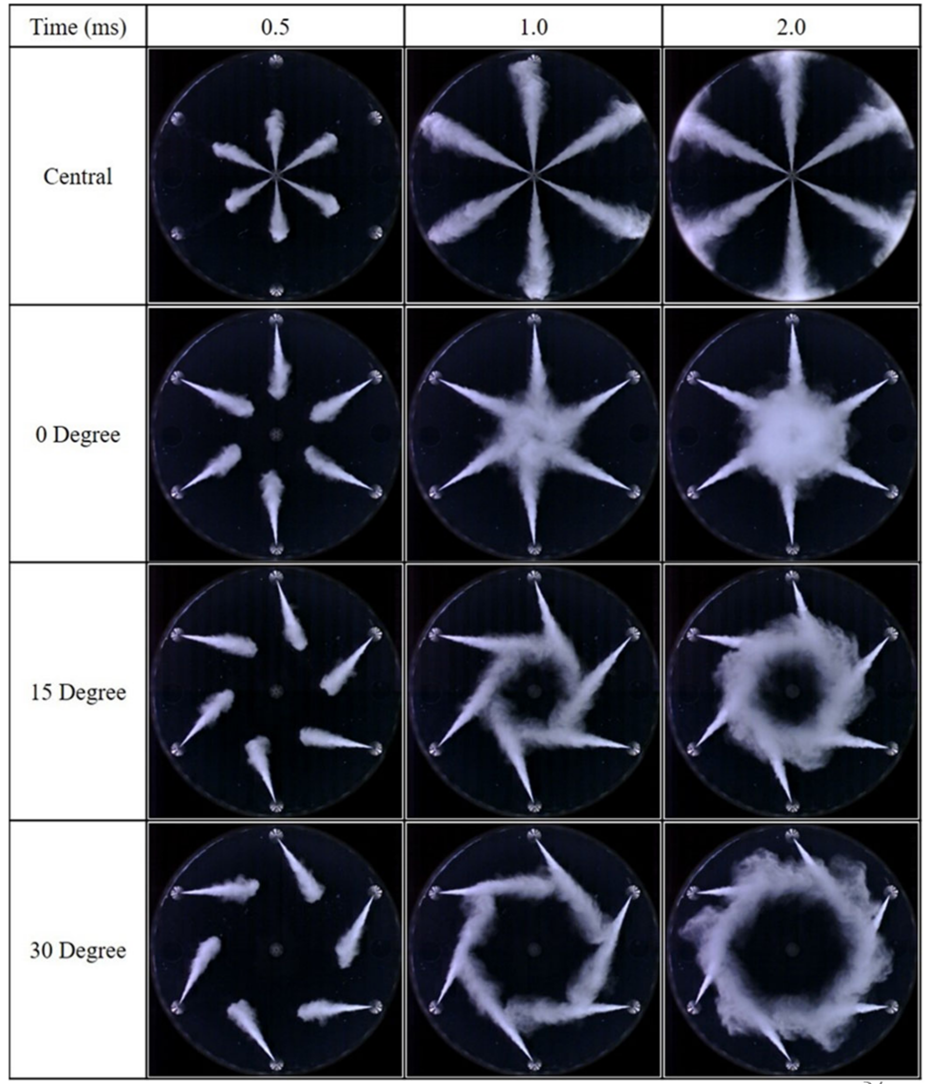
- Computed OH mass fraction at different times (top) illustrating flame impingement
- Temperature contours illustrating effects of localized hot spots resulting from flame impingement (bottom)
- What if we could eliminate wall impingement and flame interactions ?

Peripheral Fuel Injection (PeFI)

- Fuel is injected radially inwards from the periphery using multiple single-hole injectors
- No wall impingement
- Unfortunately, jets interact and form a toroidal vortex at the center
- This leads to undesirable competition for combustion air at the center

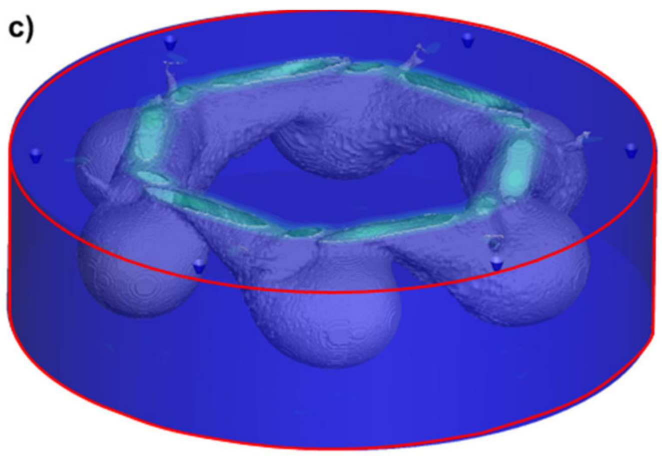
Peripheral Fuel Injection (PeFI) – Angled Injection

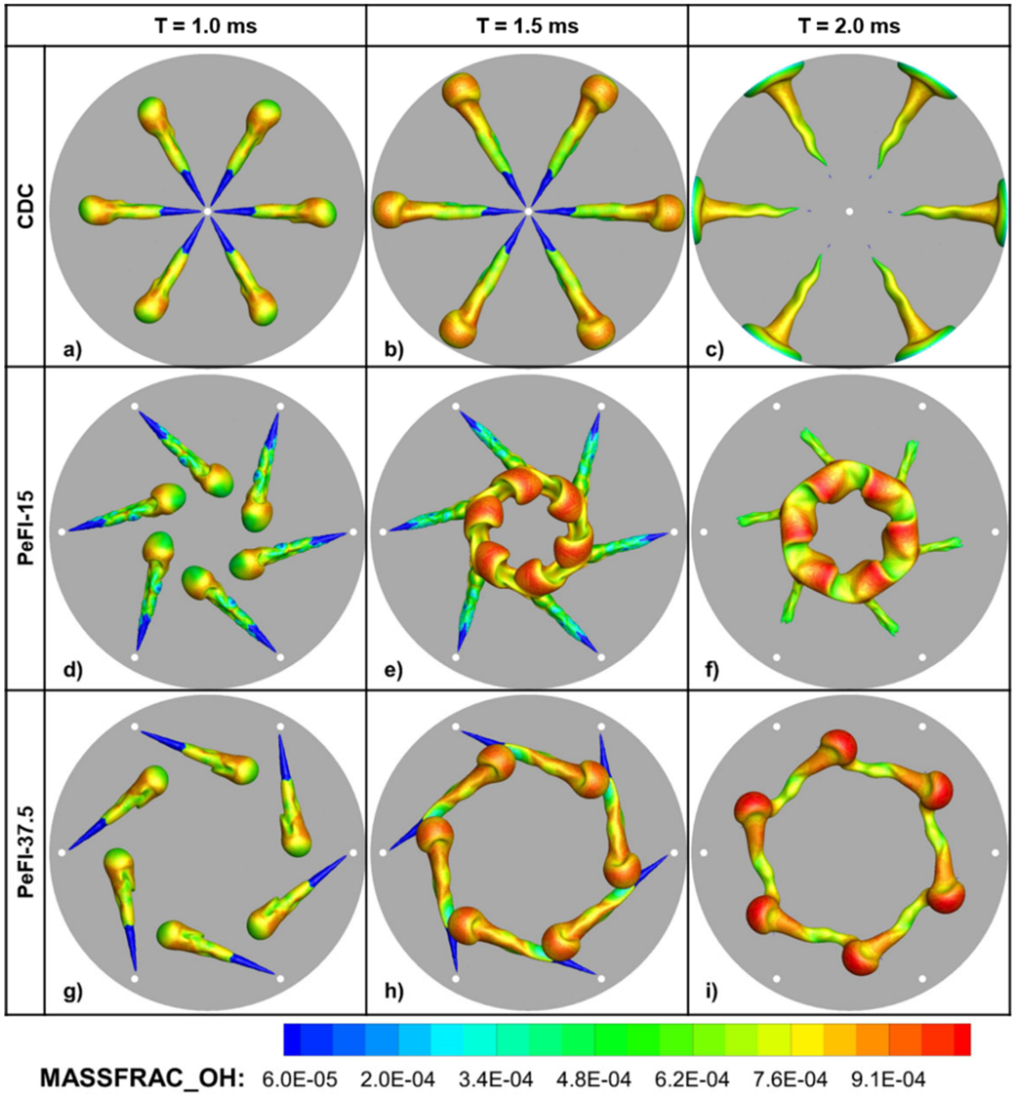
- Angled PeFI injection eliminates jet interactions
- Jets/flames remain in the outer regions to enhance access to air for both premixed and diffusion combustion modes
- Note that the jets are also orientated at an angle with respect to the screen



Angled PeFI

- Contours of OH mass fraction
- PeFI-15 injection causes flame interactions – too shallow angle
- PeFI-37.5 injection shows nearly independent flames – optimum angle
- No hot spots on the outer wall





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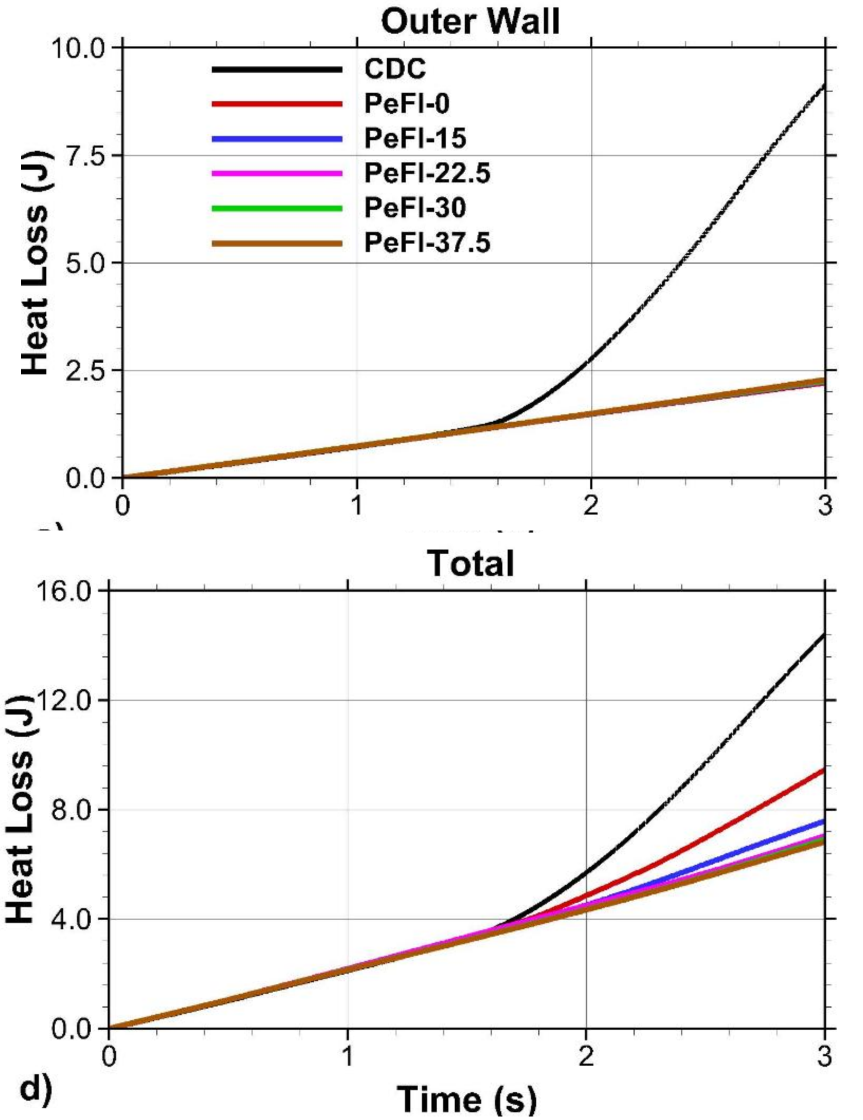
Heat Loss at Chamber Walls

- CDC: Sudden rise in heat loss after flame impingement
- PeFI: Heat loss reduction of 53% (PeFI-37.5 vs. CDC)
- PeFI creates insulated walls with a layer of ambient air, to approach near adiabatic conditions.
- The actual heat loss reduction could be even higher since simulations are based on a specified wall temperature



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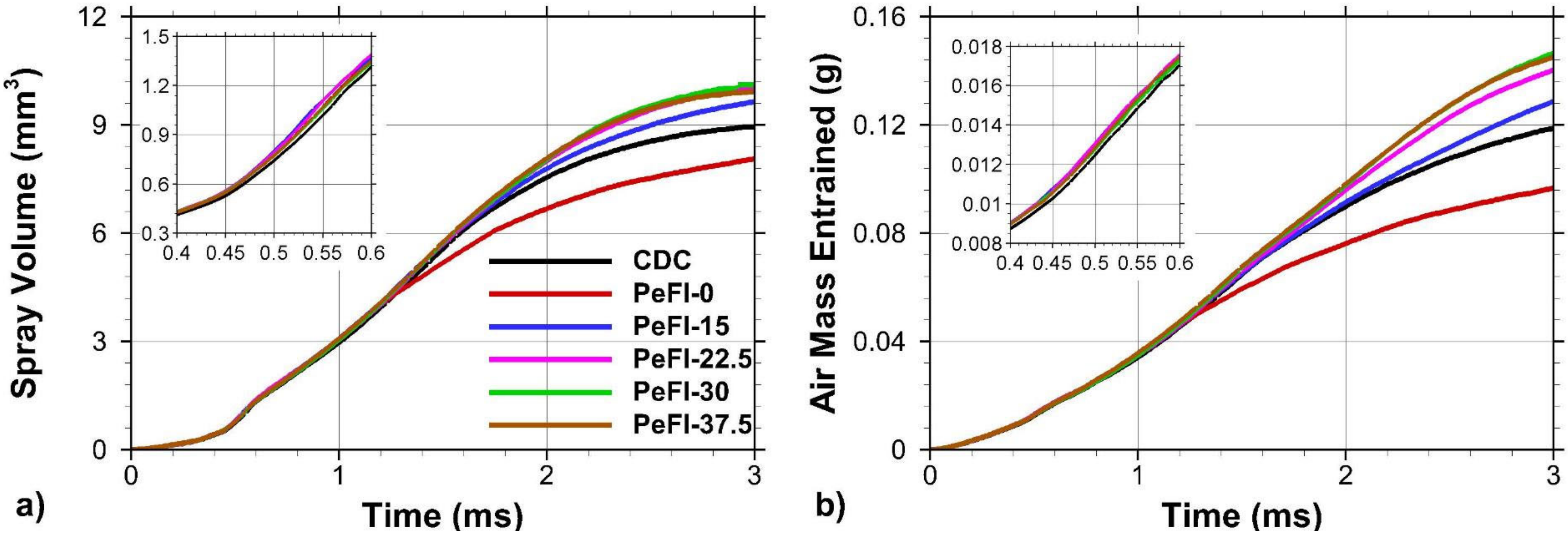
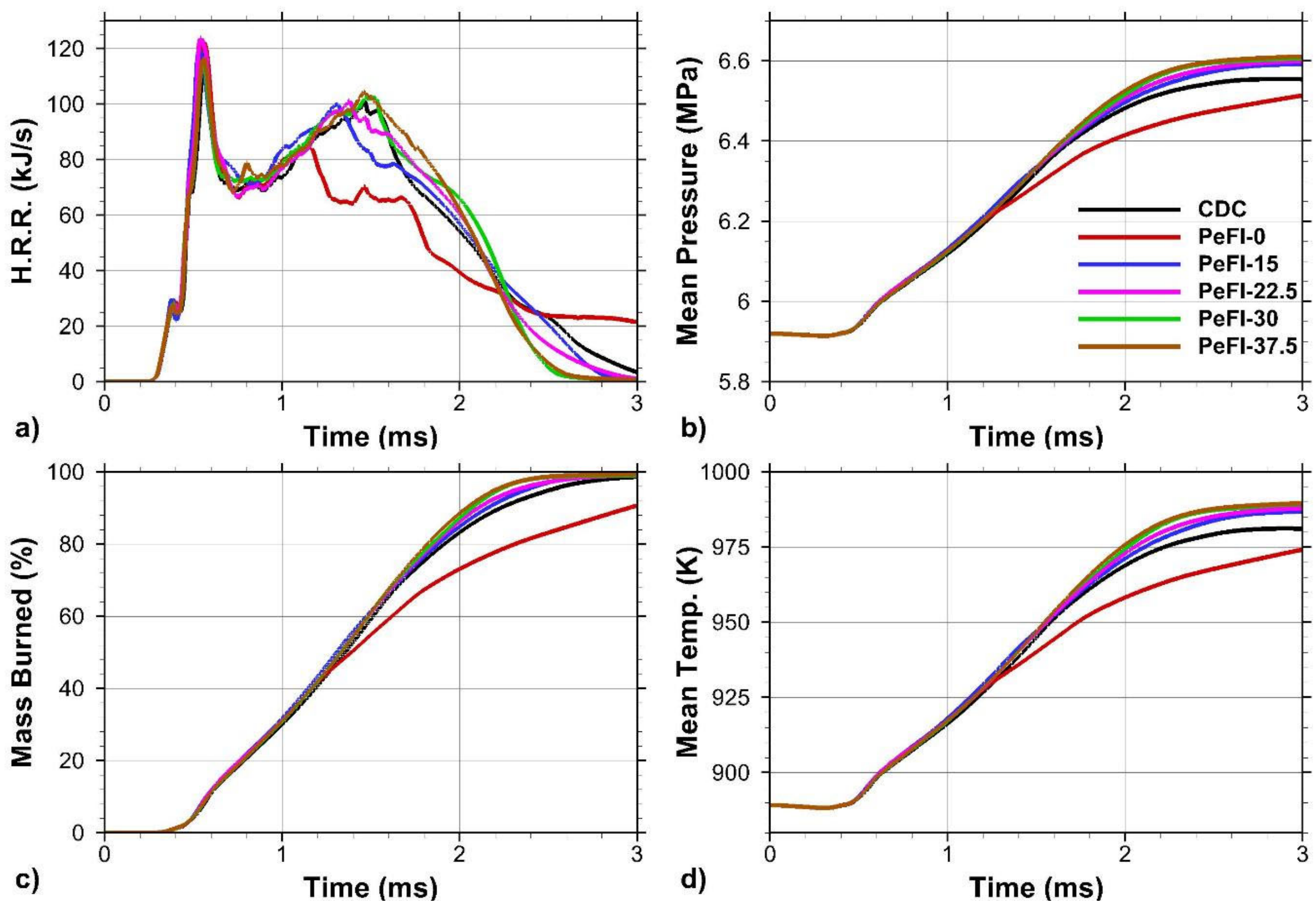
Ajay Agrawal, 2023-07-29T08:00:12.380

Air Entrainment



- PeFI-37.5 provides up to 22% more air mass entrained into the flame compared to CDC



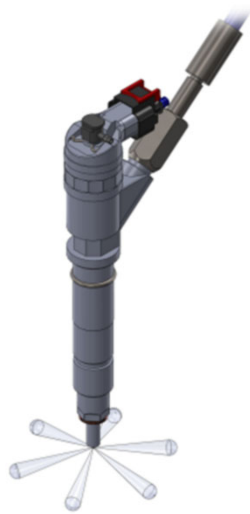
PeFI provides

- Faster HRR
- Faster burning
- Higher chamber mean pressure
- Higher chamber mean temperature
- Higher thermal efficiency (1-2%)

Fuel Rate of Injection (ROI)

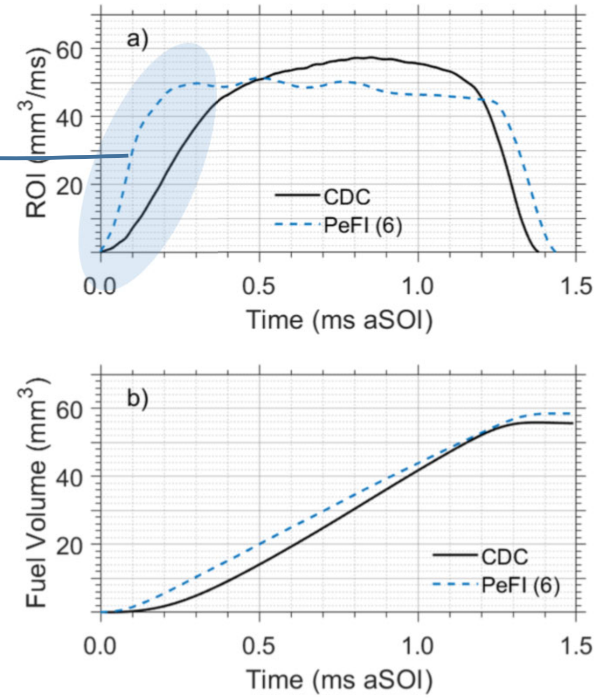
PeFI has higher ramp-up ROI

- This will improve entrainment and mixing in the near field



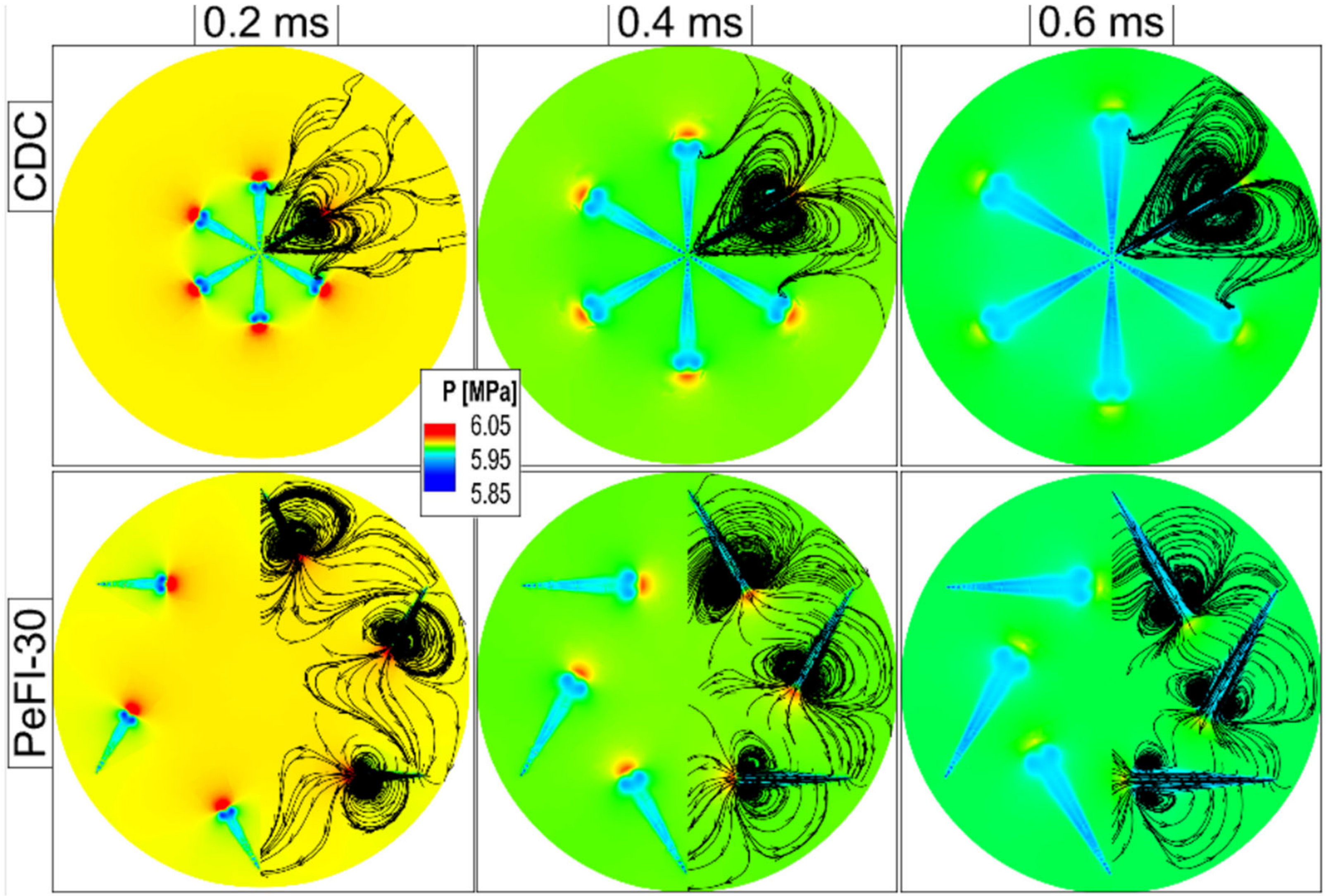
CDC injector

PeFI injector

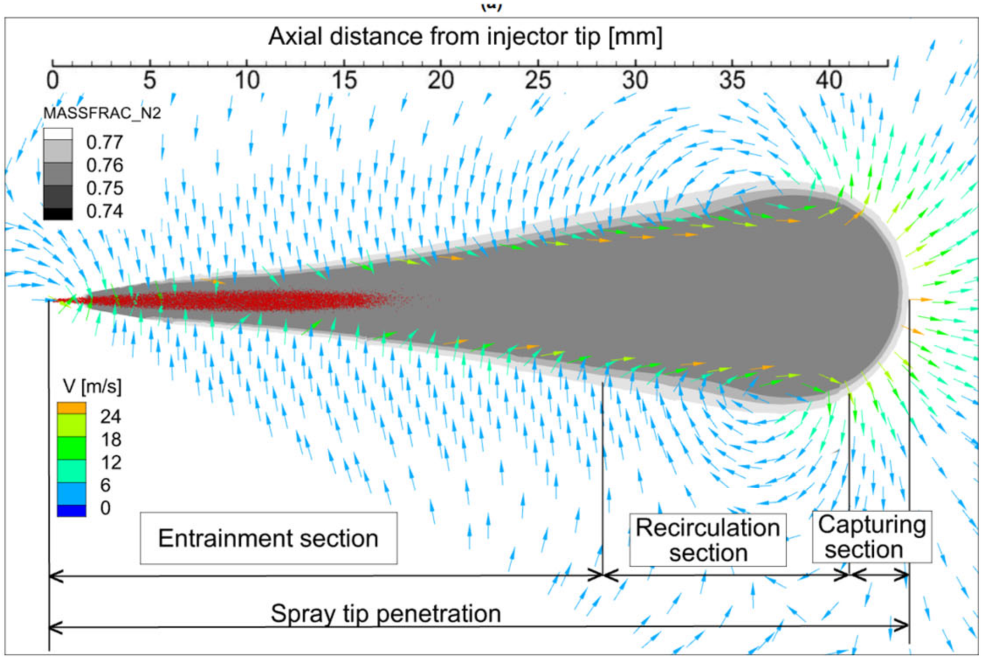


CDC and PeFI injection rates (a) and cumulative volume (b) for 1000 bar rail pressure.

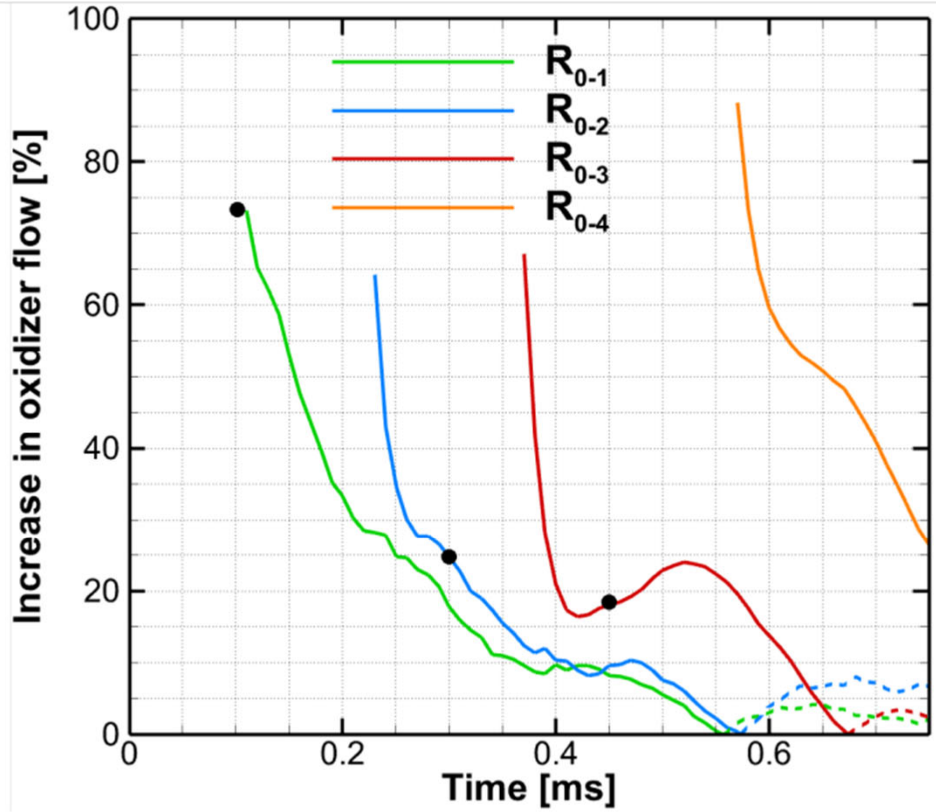
Pressure contours and stream-lines



Increase in near-field air entrainment – Reduced engine out soot emissions



(b)



PeFI Summary

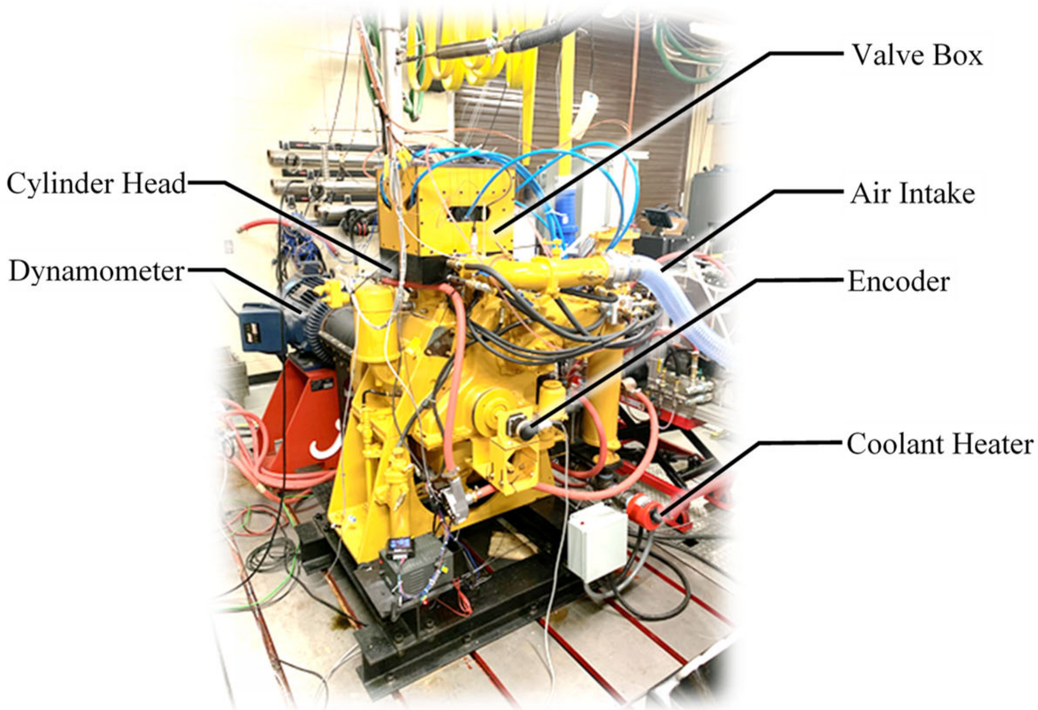
- Increased entrainment in the near-field. Leaner premixed flame at lift-off. Reduced soot precursors and engine-out soot emissions
- Flame/jet impingement on wall is eliminated. Thus, reduced soot, UHC, and CO emissions
- Significant reduction is heat loss to the coolant and thus, higher thermal efficiency
- But, can you put multiple single-hole injectors on an engine head ?

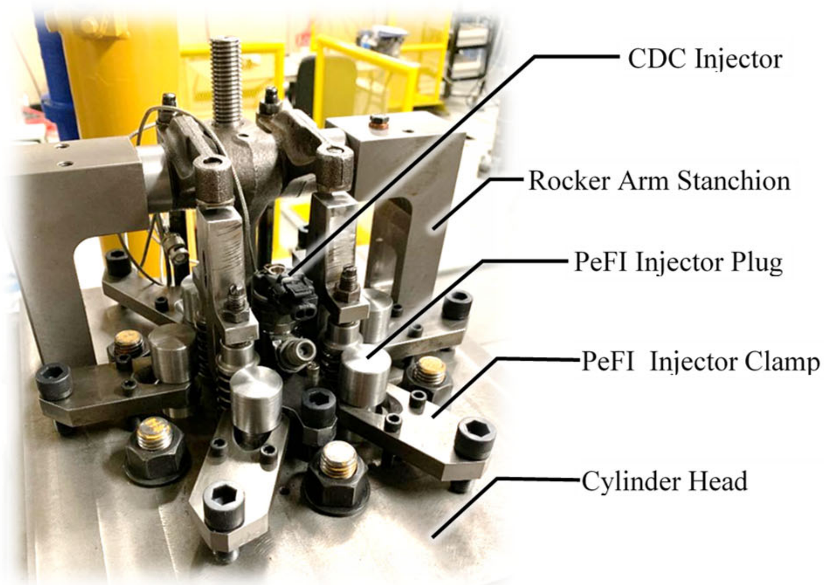
- Yes, we did it. It took several years to develop the hardware.

- We use off-the-shelf Bosch injectors.

- Ideally, we would like custom-designed injector to further miniature the system

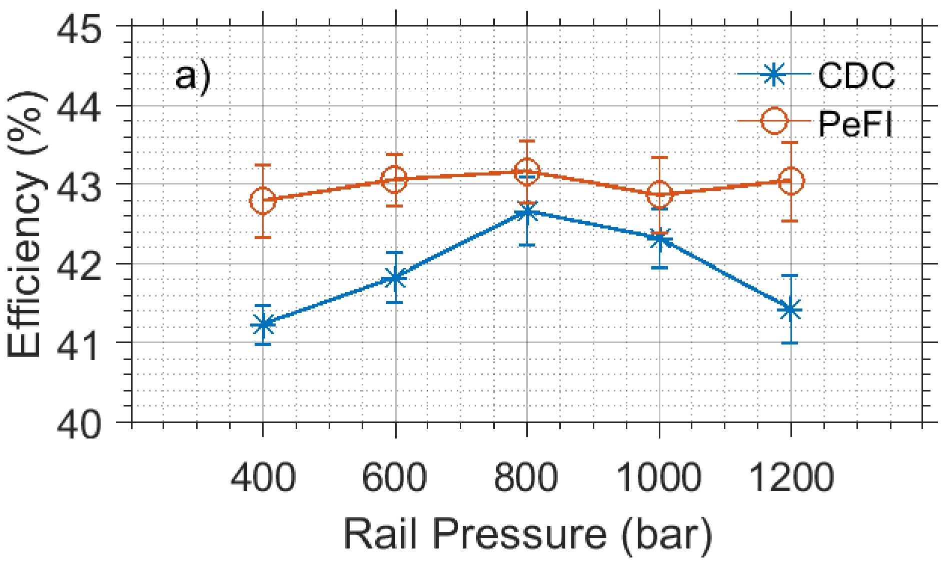
Single Cylinder Engine with Both CDC and PeFI

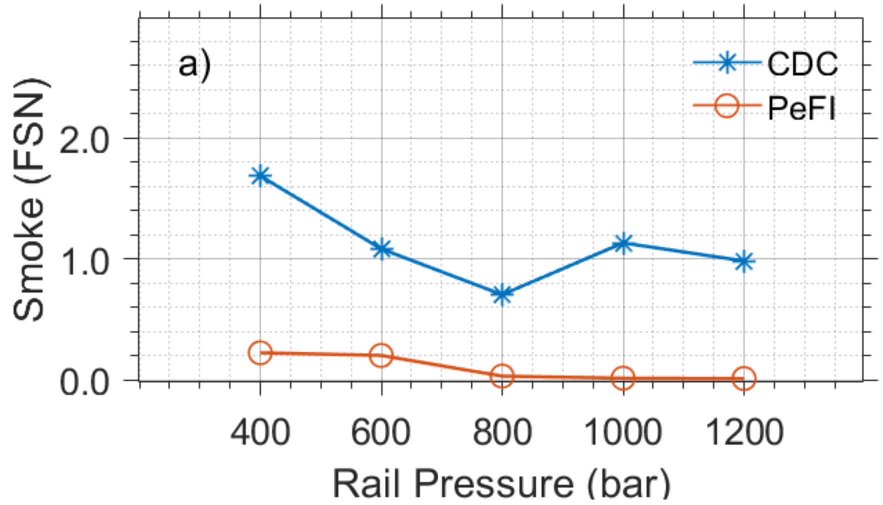


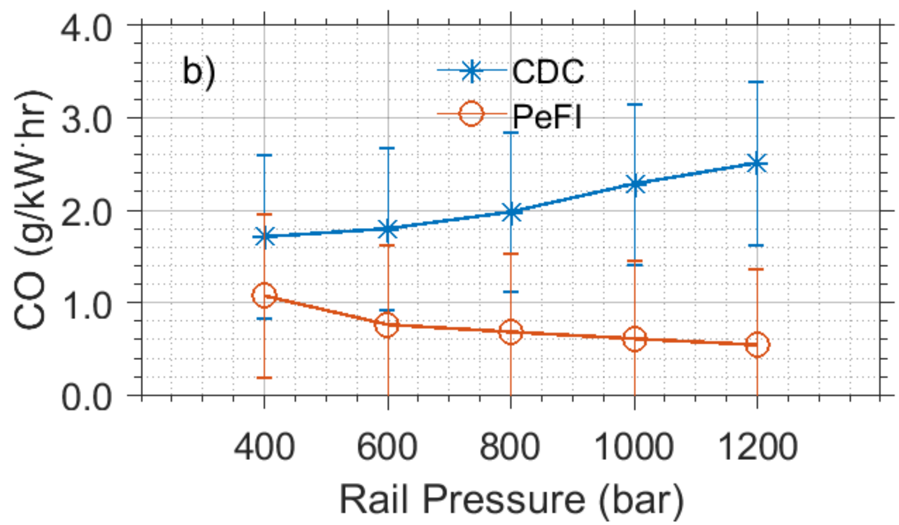


Caterpillar 3401 single cylinder engine (left) and modified head (right).

Test Results







- Higher thermal efficiency
- Negligible smoke
- Lower CO emissions
- Comparable NOx, but reductions possible
- UHC emissions require injector redesign

Summary Remarks

- PeFI opens up unparallel opportunity to improve diesel combustion and reduce need for after-treatment systems
- We have just started this journey.

- Agrawal, A.K., and Bittle, J., PERIPHERAL FUEL INJECTION FOR LOW EMISSION AND HIGH EFFICIENCY DIESEL ENGINES," U.S. Patent Application No. 63/529,925, filed July 31, 2023.

- Bogdanowicz, E.F., Loper, A., Bittle, J. and Agrawal, A.K., 2024. Experimental study of peripheral fuel injection for higher performance in diesel engines. *International Journal of Engine Research*, p.146808 74241232007.

- Edward F. Bogdanowicz, Joshua Bittle, and Ajay K. Agrawal, 2024, "Numerical investigation of peripheral fuel injection for higher performance in diesel engines," accepted, *FUEL*

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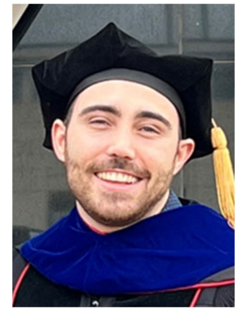

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