In-Cylinder Imaging of Conventional and Advanced, Low-Temperature Diesel Combustion

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Introduction: Diesel Optical Diagnostics

Much of our current understanding of the **in-cylinder processes** that affect <u>conventional</u> diesel combustion and emissions has been provided by **optical imaging diagnostics**.

- Over the past 2+ decades, Sandia National Laboratories has built an engine research department with **8 engines/vessels**, which have been extensively modified for optical access.
- Newly-developed laser/imaging techniques in these facilities have provided new insight into conventional diesel operation:

  1) liquid fuel spray 2) fuel vaporization 3) ignition
  4) combustion 5) soot formation 6) NO formation

Based on the optical diagnostic images, a conceptual model of conventional diesel combustion was proposed by John Dec of Sandia National Labs in 1997.

- This model has become an industry-wide standard for describing conventional diesel combustion processes.

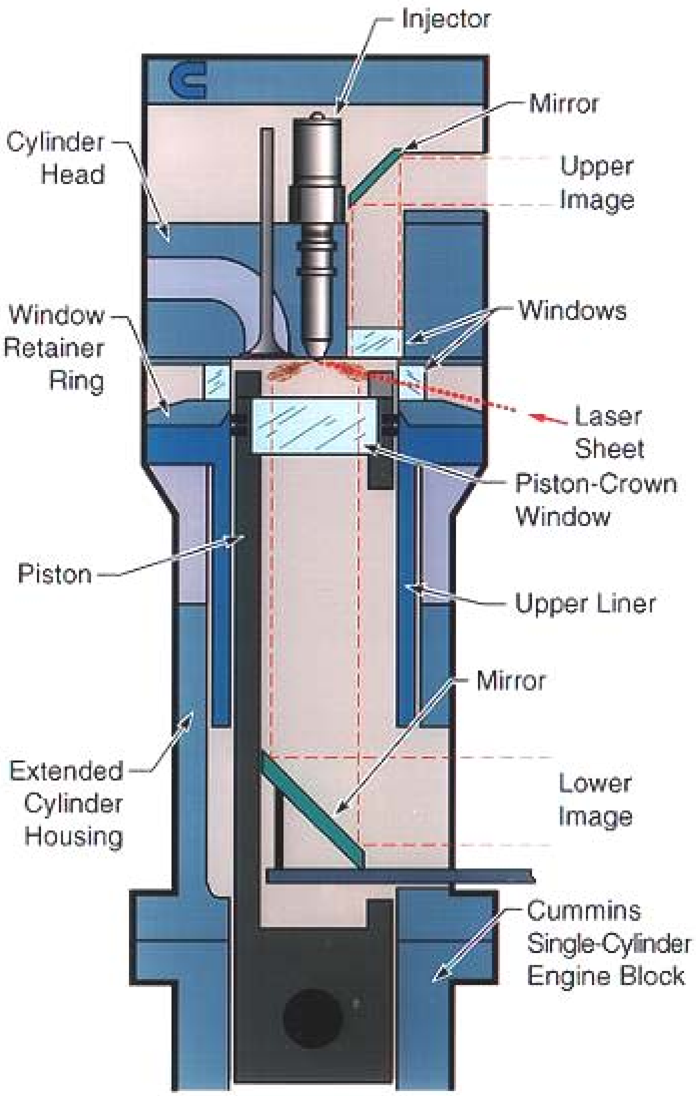
Introduction: Low Temperature Combustion

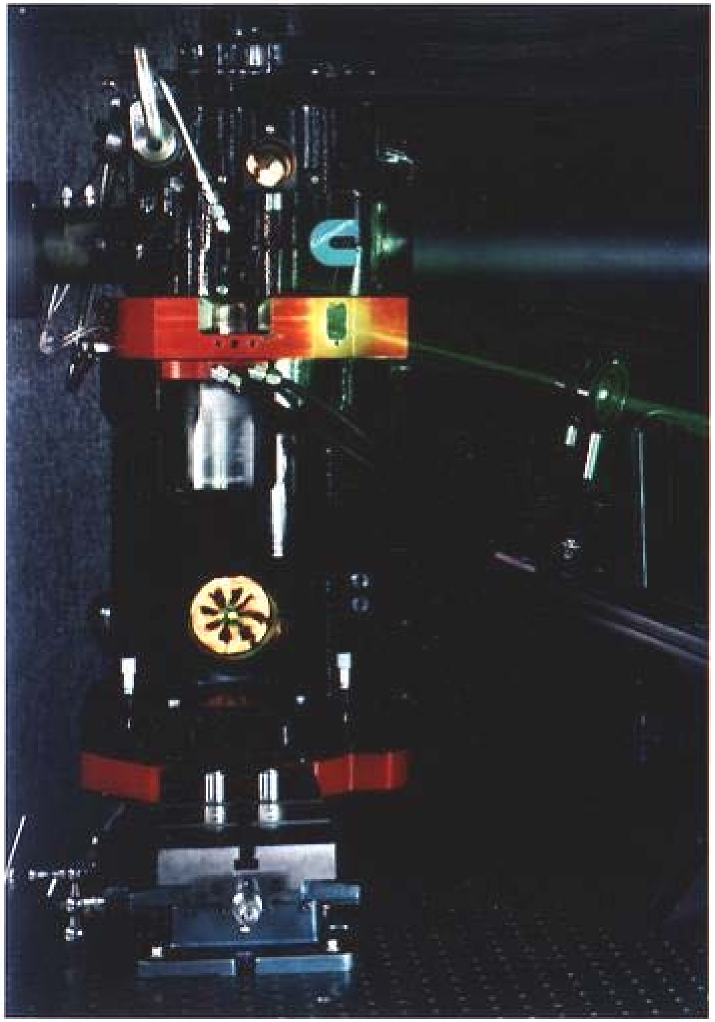
Recently, a multitude of unconventional diesel engine operating strategies (HCCI, PCCI, MK, etc.) have been proposed to meet upcoming emissions targets.

- These operating conditions reduce NO formation by achieving low temperature combustion (LTC), using either enhanced mixing with excess air to achieve lean combustion, or by dilution with exhaust gas recirculation (EGR).
- Increased mixing and/or EGR can also help to inhibit PM formation.
- Unfortunately, problems with engine control, efficiency, and other emissions (unburned fuel, CO) usually arise.

The in-cylinder processes affecting emissions and performance of these relatively new LTC operating conditions are largely unexplored by optical diagnostics!

Sandia/Cummins Optical Heavy-Duty Diesel Engine

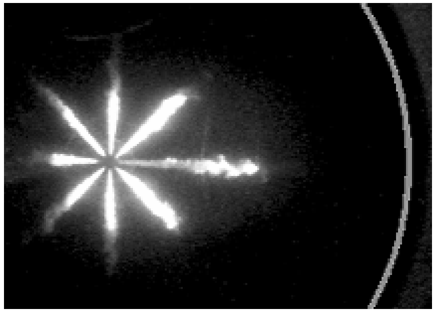




Conventional Diesel Combustion Luminosity Movie

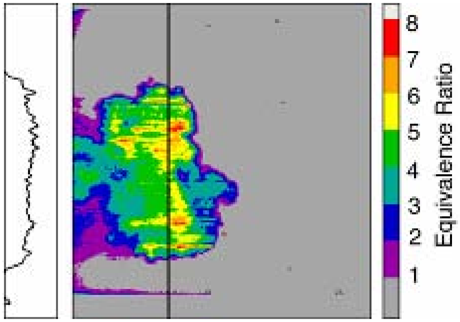
Laser Diagnostics: Conventional Diesel 1

Liquid-phase Fuel



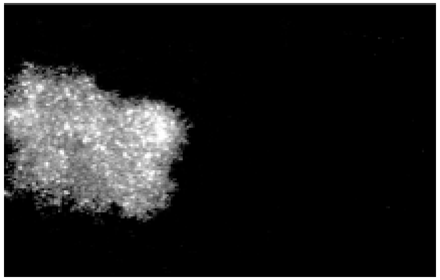
- Liquid fuel images show that all the fuel vaporizes within a characteristic length (~25 mm) from the injector.

Vapor-phase Fuel



- Vapor fuel images show that downstream of the liquid region, the fuel and air are uniformly mixed to an equivalence ratio of 3-4.

Chemiluminescence

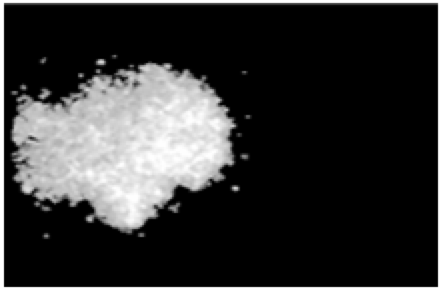


- Chemiluminescence images show autoignition occurring across the downstream portion of the fuel jet.

O_2=21%, SOI=-11 ATDC, T_{TDC} = 1000 K, ρ_{TDC} = 16.6 kg/m^3

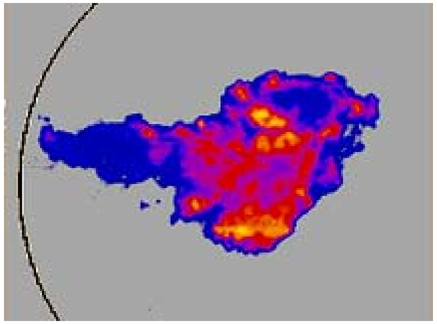
Laser Diagnostics: Conventional Diesel 2

PAH Distribution



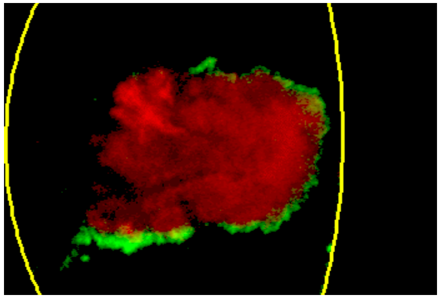
- PAHs form throughout the cross-section of the fuel jet immediately following fuel breakdown at the start of the apparent heat release.

Soot Distribution



- LII soot images show that soot forms throughout the cross-section of the fuel jet beginning just downstream of the liquid-fuel region.

OH PLIF + Soot LII

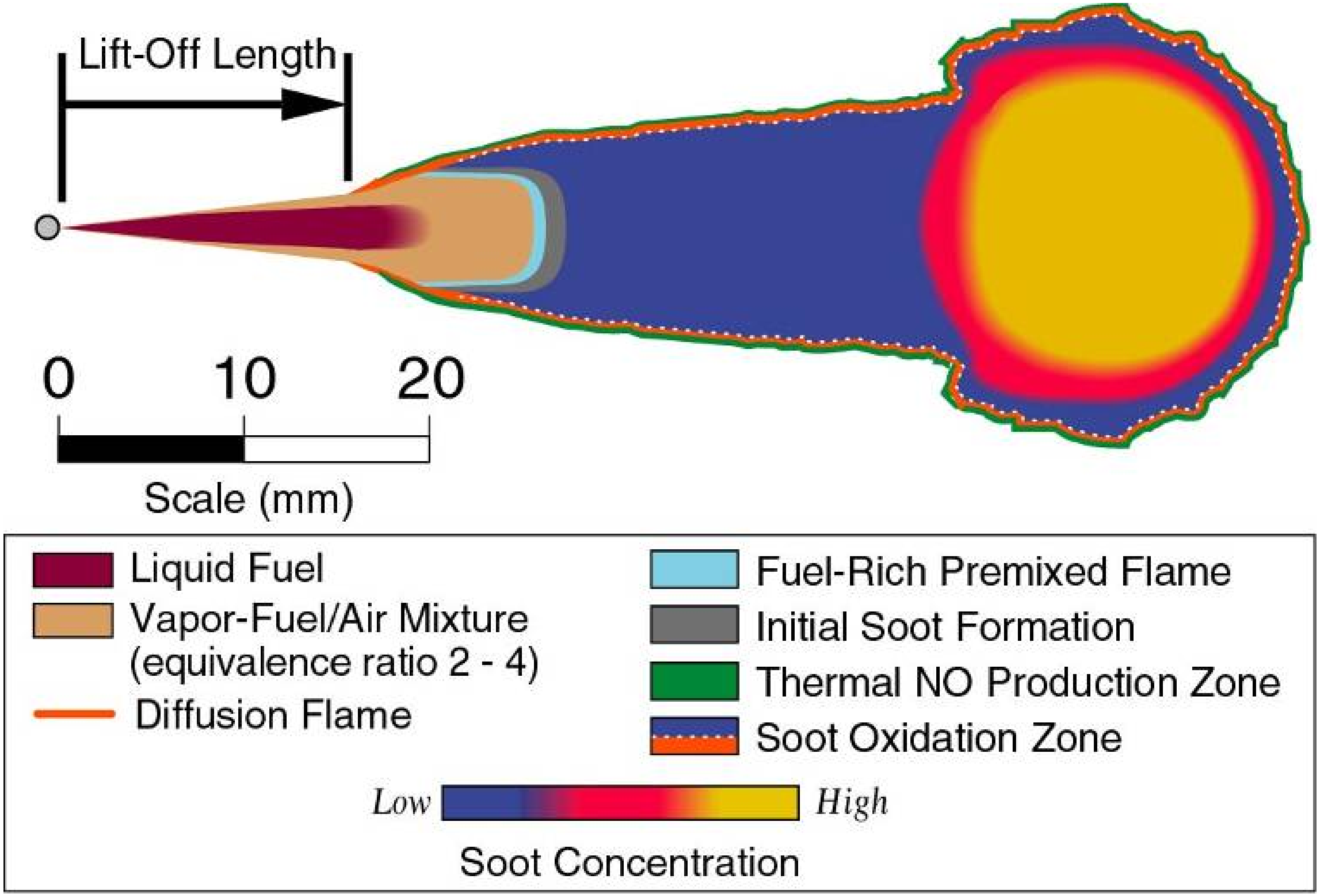


- OH images (green) show that the diffusion flame forms at the jet periphery after fuel-rich premixed combustion, which forms soot (red).

O_2=21%, SOI=-11 ATDC, T_{TDC} = 1000 K, ρ_{TDC} = 16.6 kg/m^3

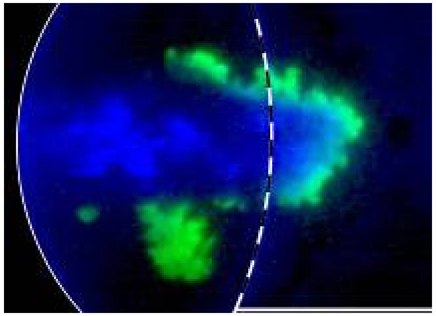
Sandia's Conceptual Model of Diesel Combustion

*From SAE 970873, J. Dec
Lift-off: SAE 2001-01-0530, D. Siebers



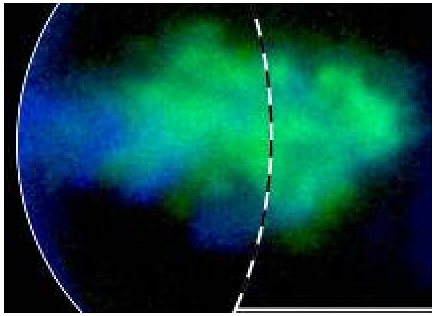
Early-Injection, Low-Temperature Combustion 1

Liquid + Vapor Fuel



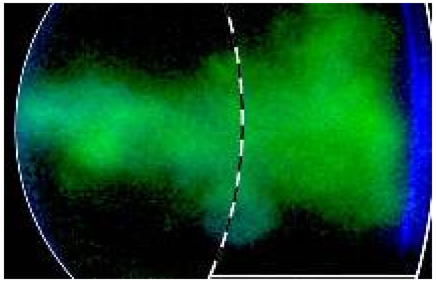
- Under the low-density conditions of early-injection, liquid fuel (blue) penetrates much farther (>50 mm), even as it vaporizes (green).

Liquid + Chemiluminescence



- Chemiluminescence from ignition reactions (green) envelopes the region containing liquid fuel (blue).

Liquid + Chemiluminescence

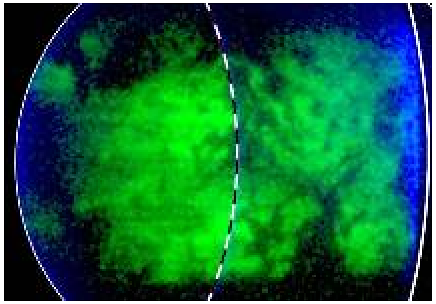


- As the chemical energy of the fuel is released (green), the liquid fuel (blue) rapidly vaporizes.

O_2=12.7%, SOI=-22 ATDC, T_{TDC} = 870 K, ρ_{TDC} = 16 kg/m^3

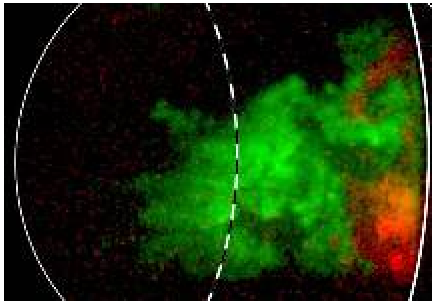
Early-Injection, Low-Temperature Combustion 2

Liquid + OH PLIF



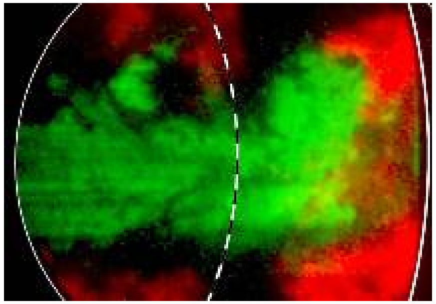
- OH (green) fills the jet cross-section shortly after ignition, indicating leaner mixtures (Φ=0.5-1.5) than conventional diesel combustion.

OH PLIF + Soot LII



- Soot (red) is first detected near the head of the jet, in regions that are deficient in OH (green).

OH PLIF + Soot Luminosity



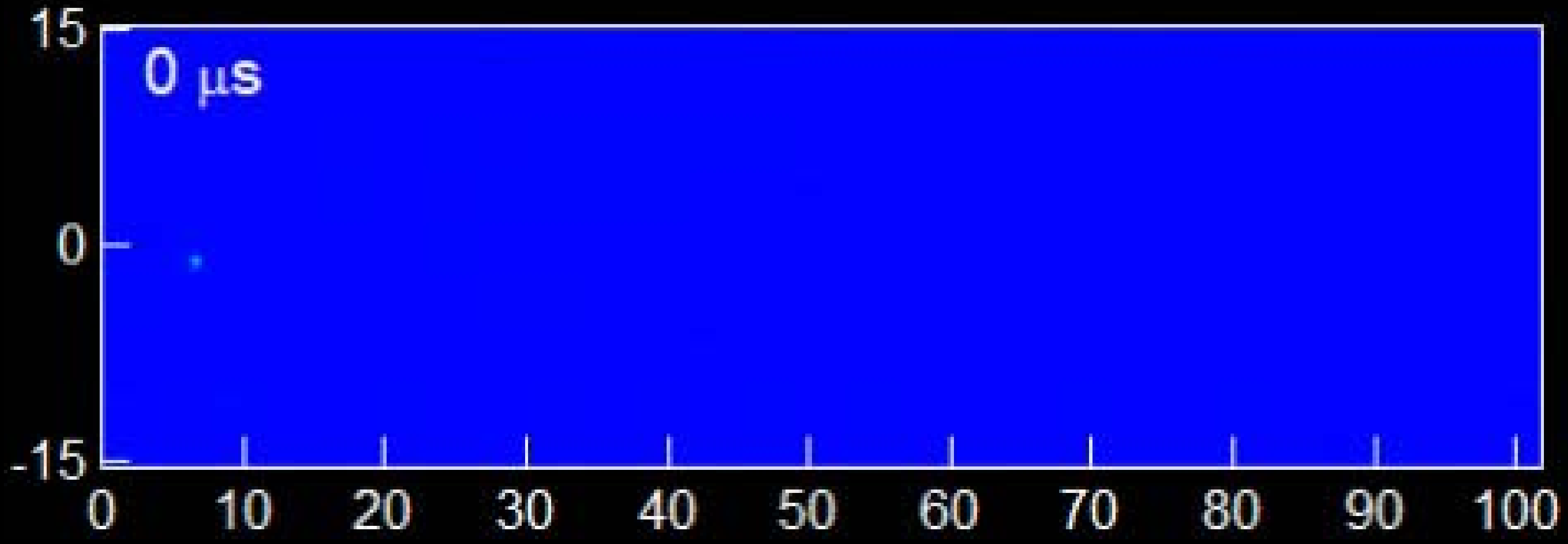
- The strongest soot luminosity (red) is often observed in the fuel rich (Φ>2) roll-up vortices at the head of the jet, enveloped by OH (green).

O_2=12.7%, SOI=-22 ATDC, T_{TDC} = 870 K, ρ_{TDC} = 16 kg/m^3

Early Injection, Low-Temperature Luminosity Movie

From Diesel Combustion Simulation Facility, Sandia Nat'l Labs, (Lyle Pickett and Cherian Idicheria)

- 1000 K, 14.8 kg/m^3, n-heptane fuel, 12% O_2
- Chemiluminescence Imaging, Red = Soot (very bright)



Summary: Early-Injection LTC Conceptual Model

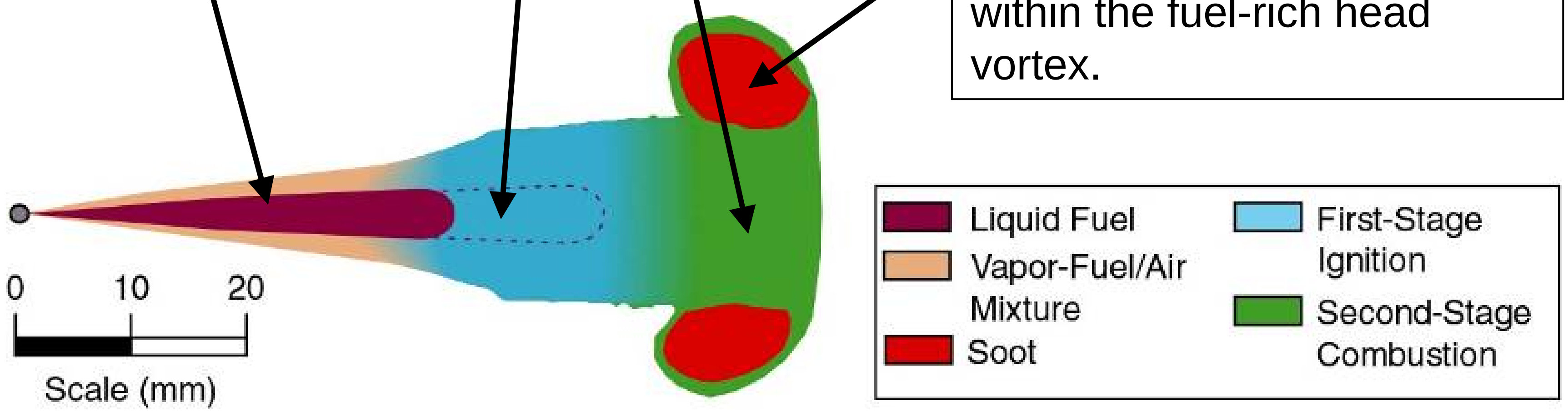
In-cylinder combustion processes of advanced, low-emissions operating conditions are significantly different from conventional diesel combustion.

Energy released by fuel ignition reactions contributes to the vaporization of liquid fuel.

Liquid fuel penetrates much farther into the cylinder, potentially wetting surfaces. (may cause HC, PM emissions)

Well-mixed combustion occurs throughout the jet cross section, preventing soot there.

If it forms at all, soot is only found at the tip of the jet, within the fuel-rich head vortex.



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