Visualization of UHC Emissions for Low-Temperature Diesel Engine Combustion

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Optical Diagnostics and UHC in LTC

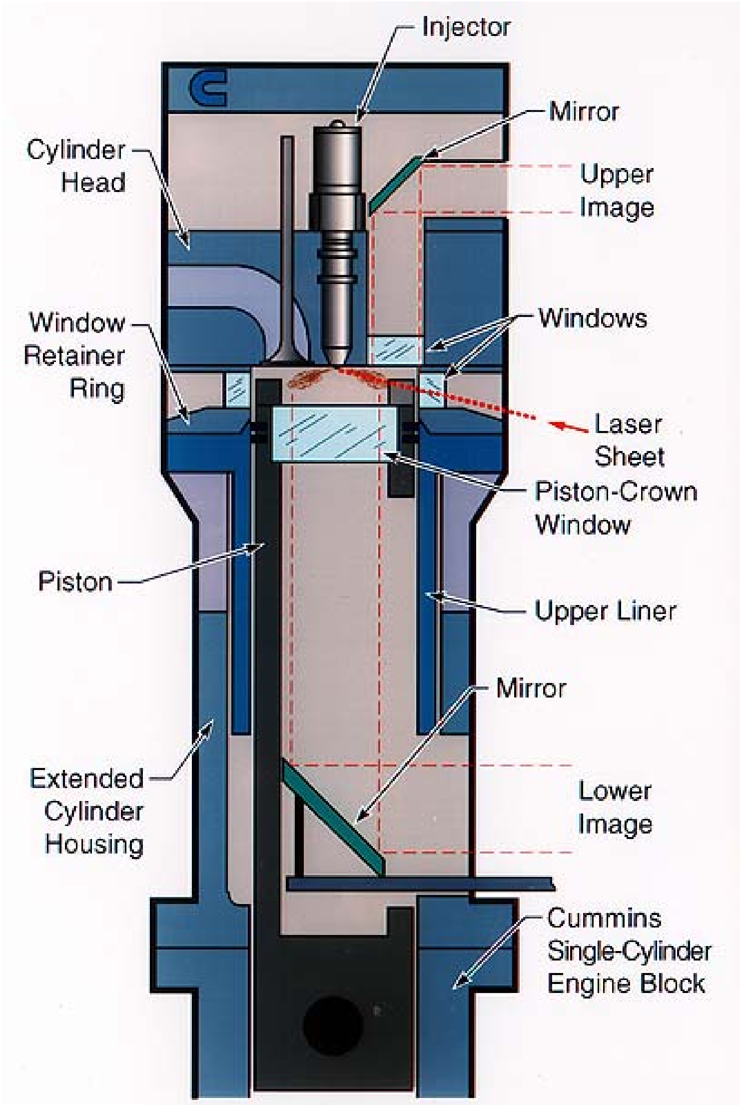
Understanding of in-cylinder processes, where much of combustion in *conventional diesel conditions* occurs *during a quasi-steady jet period*, has been provided by optical imaging diagnostics.

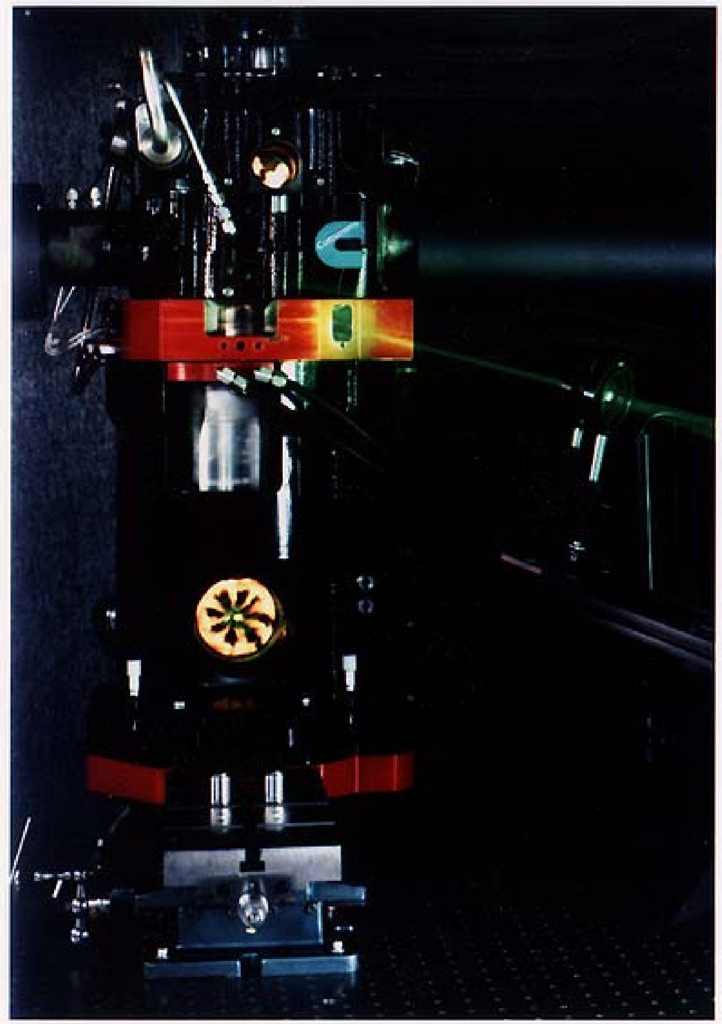
- Over the past 20+ years, the Combustion Research Facility (CRF) at Sandia National Laboratories has built an engine research department with 7 engines/vessels, which have been extensively modified for optical access.

For advanced low-NOx, low-PM engines, combustion in many of these *unconventional diesel conditions* occurs *after a transient jet period*, using lean premixed combustion and/or dilution with exhaust gas recirculation (EGR) to achieve **low temperature combustion (LTC).** (HCCI, **PCI**, CAI, MK, etc.)

- Unburned fuel (UHC) and CO emissions typically increase, but in-cylinder mechanisms are yet to be identified and understood (wall-wetting, over-mixing, bulk-gas quenching, others?)

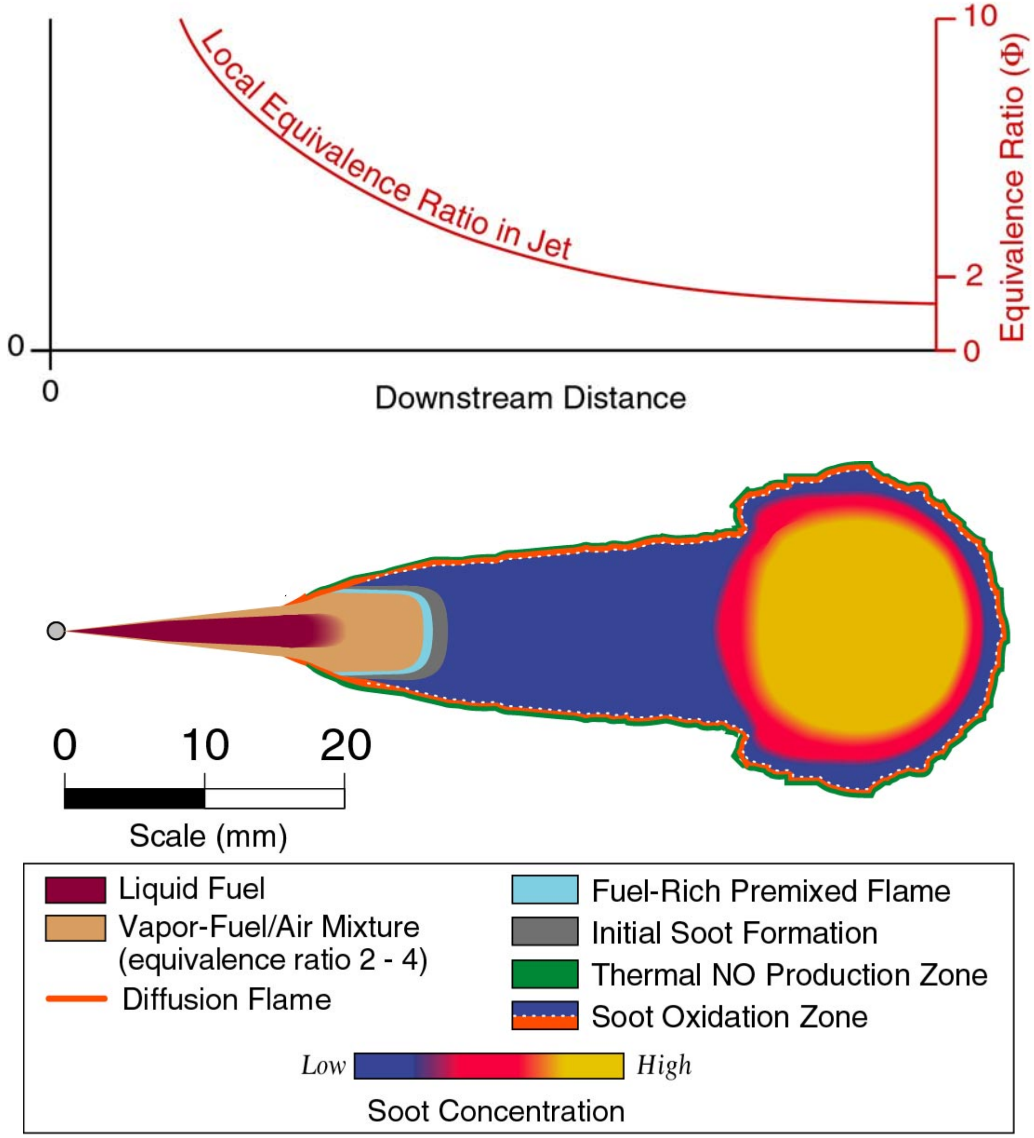
Sandia/Cummins Optical Heavy-Duty Diesel Engine





Conventional Diesel Combustion Luminosity Movie

Sandia's Conceptual Model of Diesel Combustion



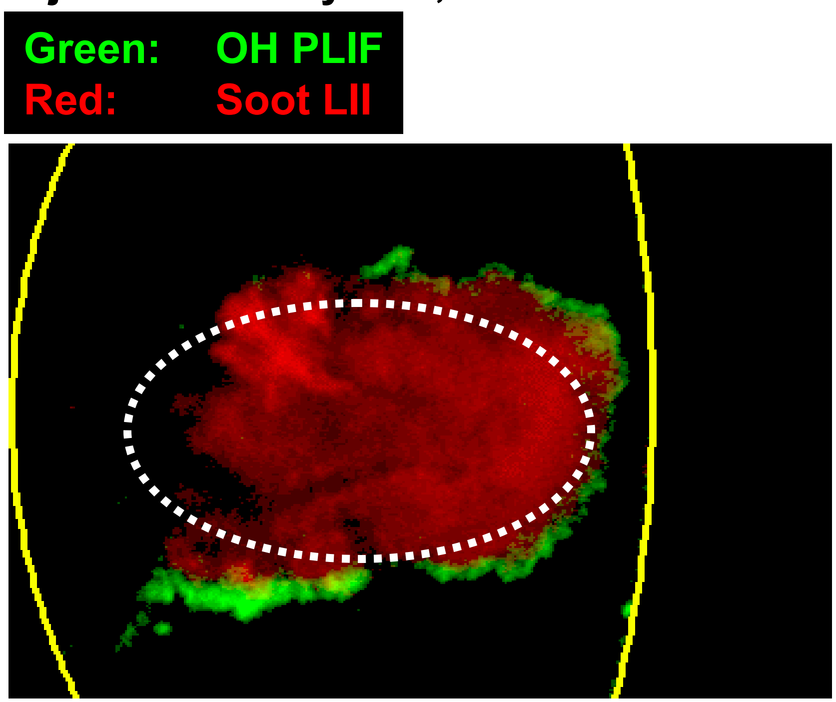
*From SAE 970873, J. Dec

- The **<u>local</u>** "equivalence ratio" (Φ) describes the fuel/air balance in the jet (1 = stoichiometric).
- **Closer to injector, a <u>steady jet</u> is fuel-rich (Φ>>1).**

Comparison of Conventional and LTC (DEER 2005)

Conventional Diesel Combustion:

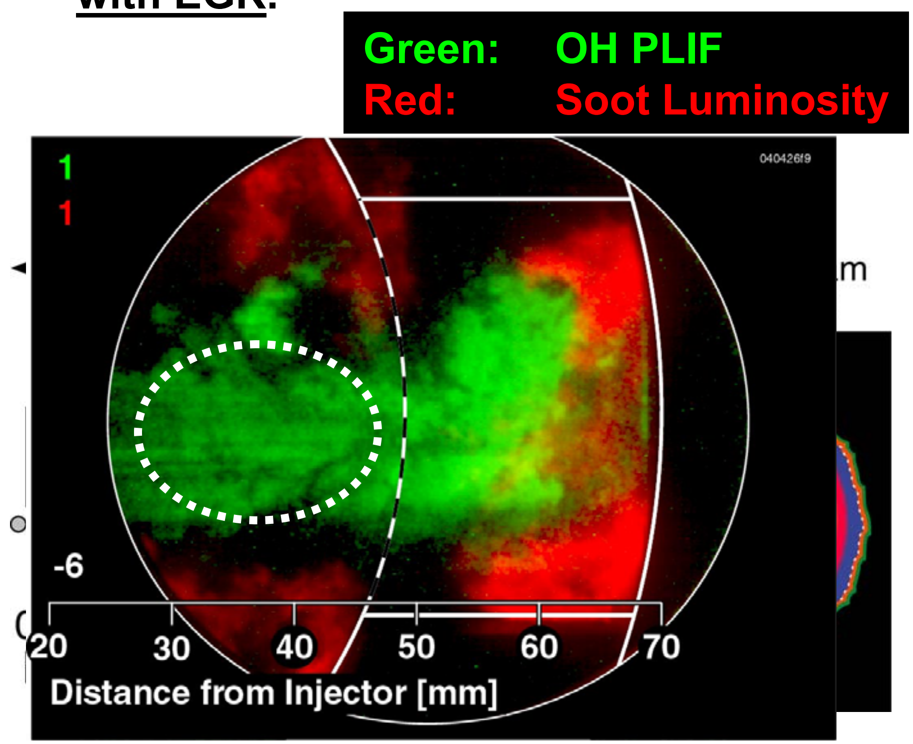
- No EGR (21% O_2), short ignition delay *(combustion during quasi-steady jet)*
- OH **(green)** in thin envelope surrounding soot **(red)** throughout the jet cross section.
- OH exists only in a thin region near Φ=1.
- Soot only forms in fuel-rich regions, so **jet is relatively rich, even without EGR.**



*From SAE 2001-01-1295, J. Dec

Early Injection LTC (PCI):

- High EGR (12.7% O_2), long ignit. delay *(combustion after transient jet)*
- OH (green) throughout jet cross-section, with soot (red) only at head of jet.
- OH only persists in near-stoichiometric regions, **so jet is relatively lean, <u>even with EGR</u>**.



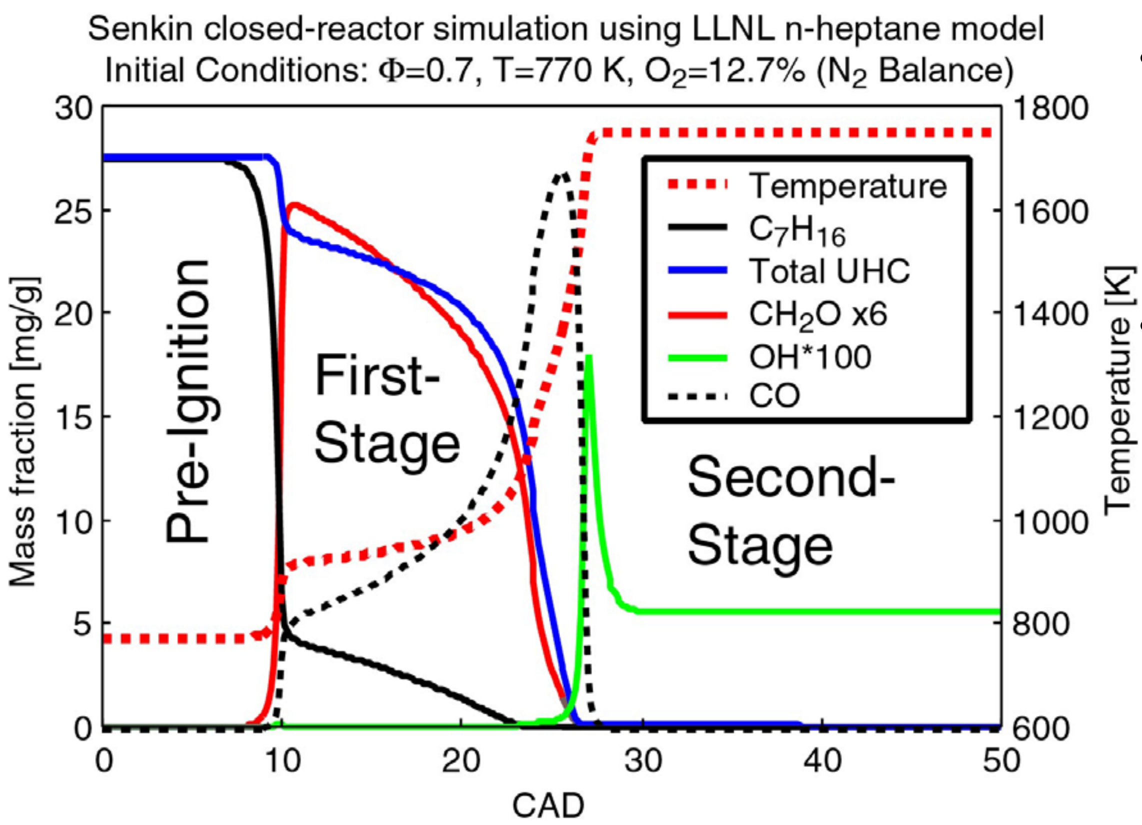
Formaldehyde as Marker for UHC and CO

Direct detection of unburned fuel with optical diagnostics is difficult.

- "Soup" of fuel fragments formed during ignition, tracer chemistry, etc.

Alternative: use intermediate species formed in two-stage ignition process

- Formaldehyde forms during first stage, consumed in second (fuel too).
- Fuel +O_2 → Formaldehyde (CH_2O) + CO + UHC → OH → CO_2 + H_2O



- For LTC conditions, formaldehyde curve is similar to UHC "soup" after first stage of ignition.
- UHC and CO are oxidized along with formaldehyde during second stage.

Formaldehyde is therefore a marker of UHC that has reached first stage ignition.

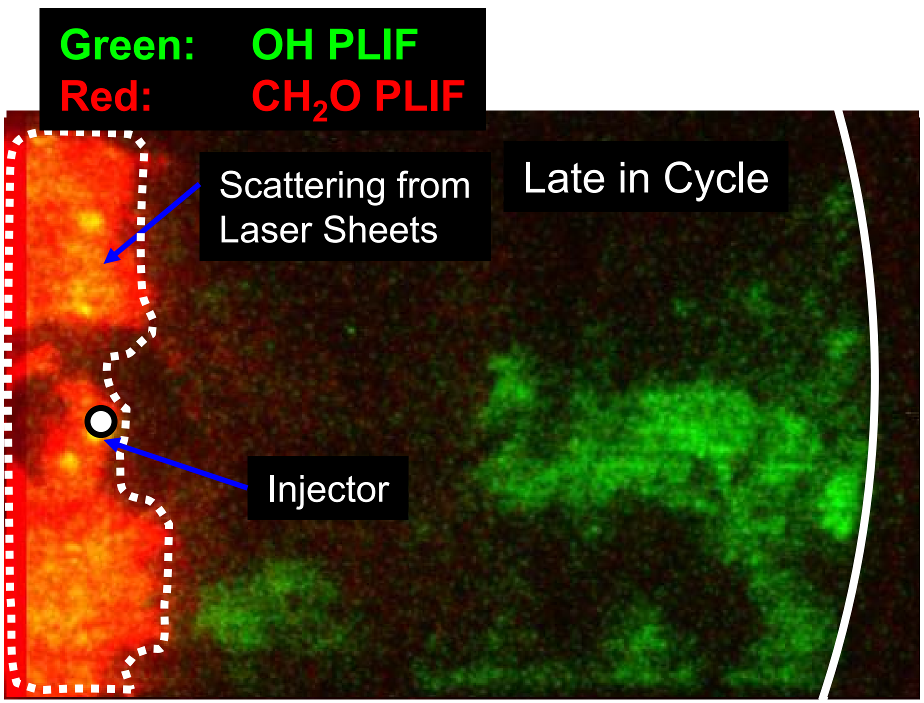
Formaldehyde PLIF Shows UHC for LTC

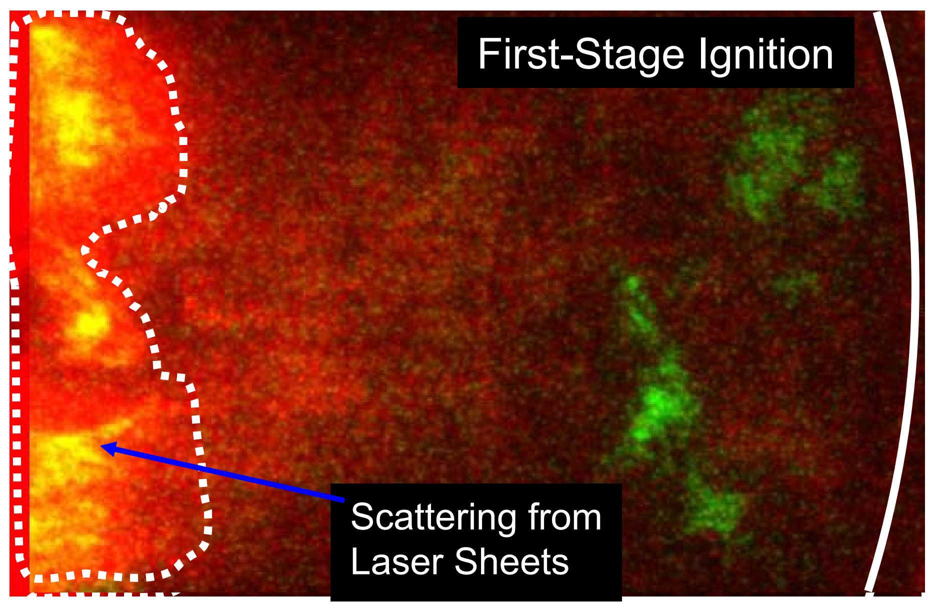
Conventional Diesel Combustion:

- High EGR (12.7% O_2), short ignition delay *(combustion during quasi-steady jet)*
- Formaldehyde (CH_2O, red) appears in jet during first-stage ignition.
- Later, OH (green) appears and consumes CH_2O throughout jet.
- No late-cycle CH_2O, no exhaust UHC

Early Injection LTC:

- High EGR (12.7% O_2), long ignition delay *(combustion after transient jet)*
- Formaldehyde (CH_2O, red) appears in broad distribution during first stage ignition.
- Later, OH (green) appears downstream only, consuming CH_2O downstream
- CH_2O remains late in cycle, especially near injector, and exhaust UHC is high





Late Formaldehyde Suggests Lean Mixtures

Chemical kinetics model shows formaldehyde persists in lean mixtures.

- For LTC conditions with *combustion after the transient jet*, these lean mixtures (Φ<1) are near the injector. This is the direct opposite of *combustion during the quasi-steady jet*, where Φ>>1 near injector.
- Incomplete combustion of lean mixtures near injector (over-mixing) is likely an important source of UHC and CO for LTC conditions with *combustion after the transient jet*.

Other evidence of lean mixtures and/or UHC emissions:

1. Correlation between late-cycle formaldehyde and exhaust UHC
2. Late-cycle OH-PLIF interference near injector (UHC?)
3. Quantitative equivalence ratio measurements using both Rayleigh scattering and toluene fluorescence (preliminary) show Φ<<1 near injector after end of injection

Fundamental Water Jet Study Provides Some Insight

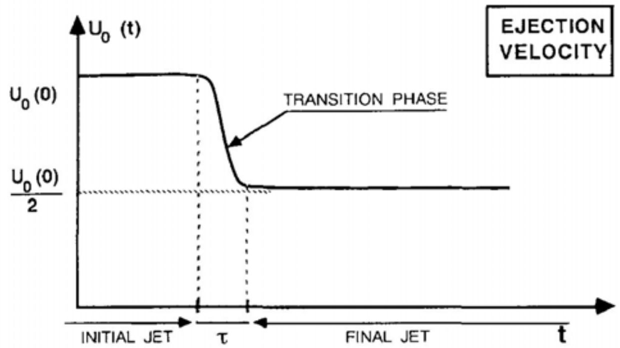
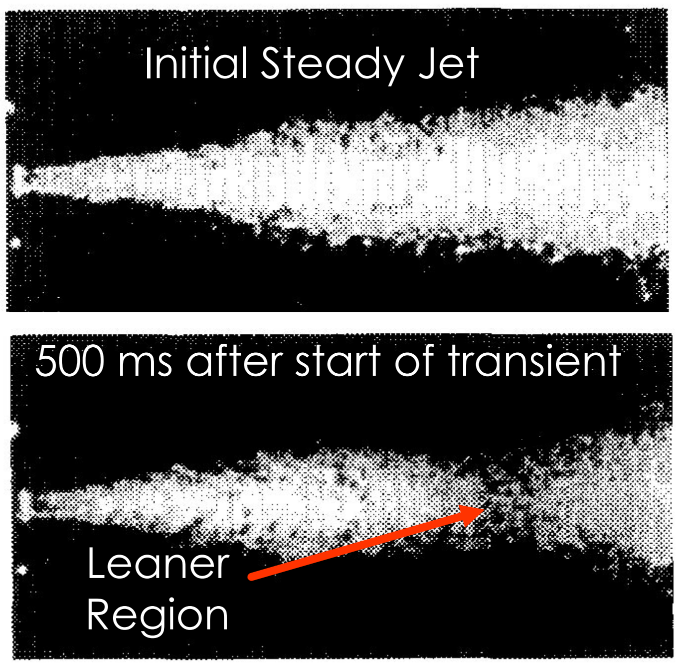


Figure 1. Typical temporal evolution of the ejection velocity.



From: "Measurements and Image Analysis of the Turbulent Field in an Axisymmetric Jet Subject to a Sudden Velocity Decrease," Boree et al., Experimental Thermal and Fluid Science, 1997

- Dyed water jet injected into water tank with initial high velocity, then transition to lower velocity.
- Fluorescence imaging of dyed jet shows **leaning of mixture** within the transition phase as it propagates downstream.
- Streamwise length of the transition phase (separation between high- and low-velocity jet flow) increases as the jet penetrates downstream (increasingly larger region of lean mixtures with time).

Conclusions

- End-of-injection transient may be critical for controlling UHC and CO emissions in PCI LTC:
  - Optical engine diagnostics and fundamental jet-mixing studies show that end-of-injection yields lean mixtures
  - If combustion occurs *during the quasi-steady jet period*, downstream combustion may propagate upstream to consume fuel and CO near the injector **before** mixtures become too lean, so UHC emissions are low
  - If combustion occurs *after the transient jet period*, ignition and combustion may occur **after** mixtures near the injector become too lean to reach complete combustion, so UHC emissions are high

Conventional vs. LTC Combustion Luminosity Movies

Conventional Diesel Condition

(combustion during quasi-steady jet)

At end of injection, sooty combustion propagates back to injector, consuming fuel

LTC Condition

(combustion after transient jet)

Sooty combustion remains near periphery of piston bowl, and fuel near injector may not burn

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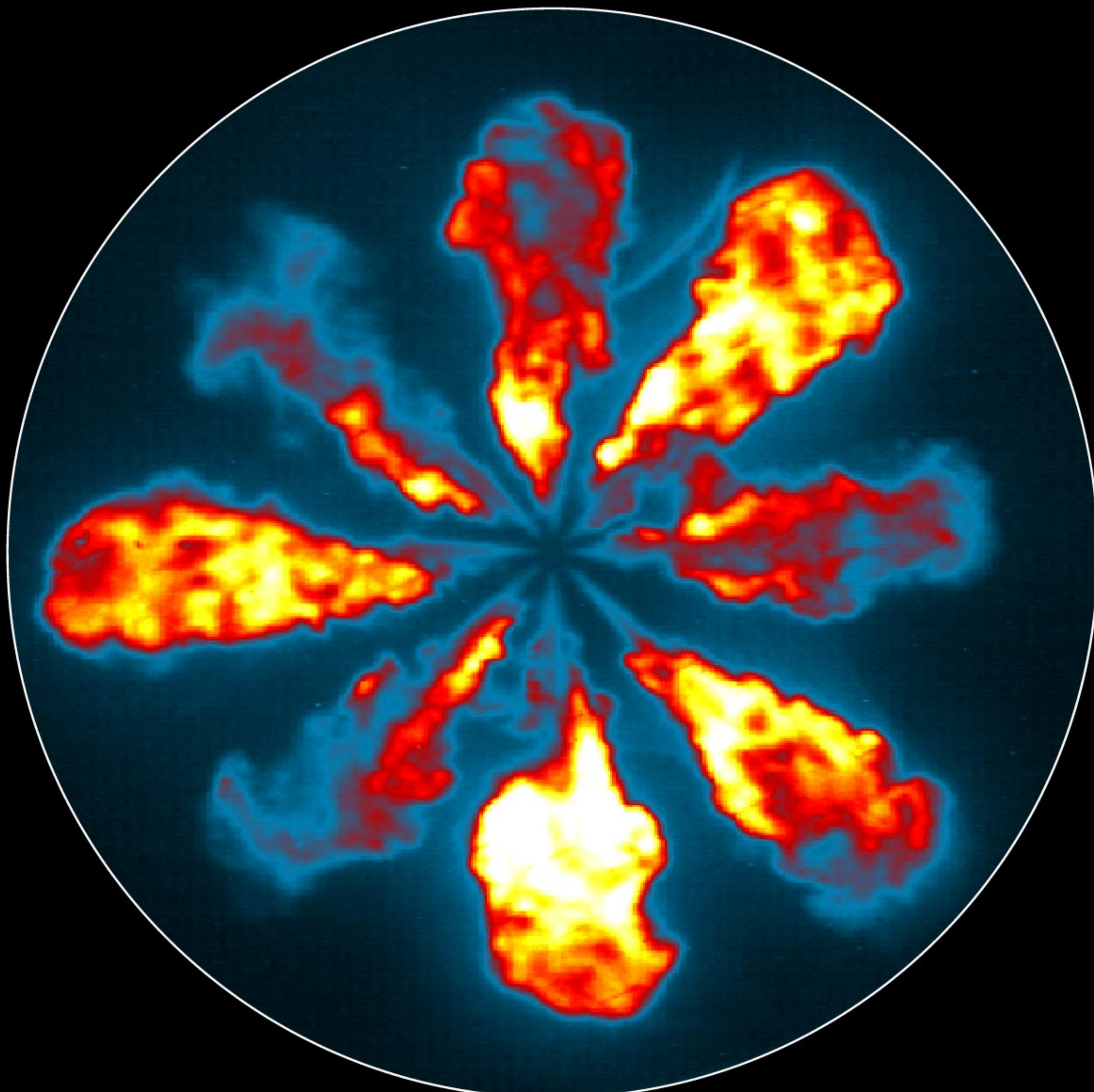
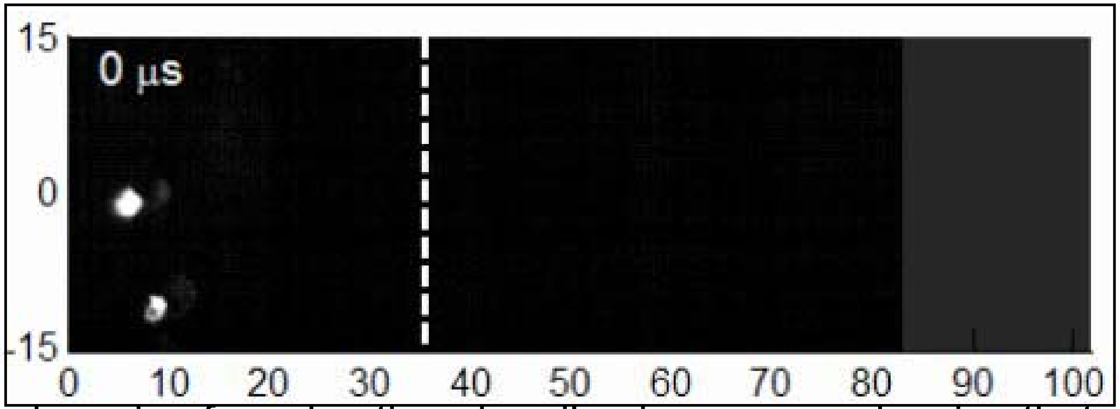
- Next Step:
  - Use quantitative optical diagnostics to assess how much the of the end-of-injection transient contributes to total exhaust UHC emissions (how much UHC is in these mixtures?)

End of slide show

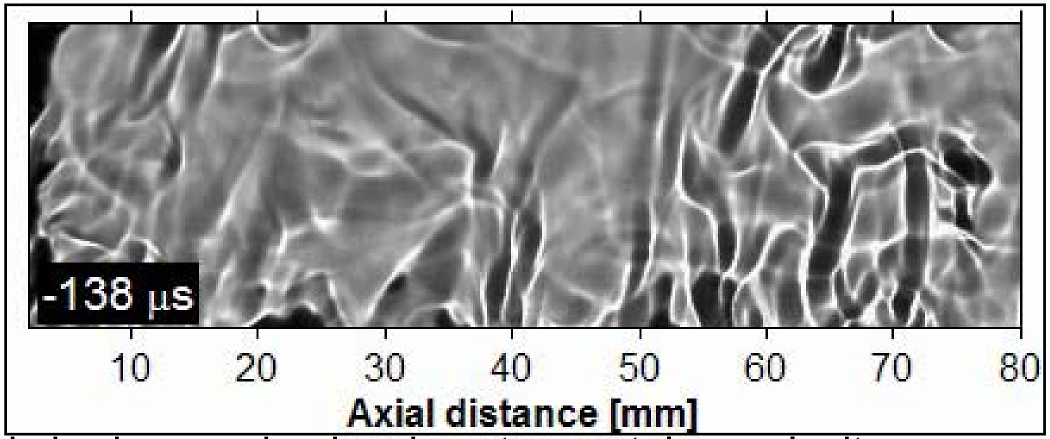


Diesel Jet Processes in Constant-Volume Vessel

From Sandia Diesel Combustion Simulation Facility,
Lyle Pickett and Cherian Idicheria



High-speed movie of combustion chemiluminescence, showing that combustion does not propagate upstream after end of injection



High-speed shadowgraph, showing stagnant, low-velocity gases near injector after the end of injection, while downstream gases have higher velocities.

Summary

- *Conventional diesel conditions:* combustion *during quasi-steady jet period*:
  - Jet is overall fuel-rich, with richer regions close to injector
  - Significant soot forms within the jet, consistent with fuel-rich mixtures
  - Formaldehyde is created during ignition, but is consumed quickly, and UHC and CO emissions are low
- *Unconventional LTC conditions:* combustion *after the transient jet period*:
  - OH is plentiful throughout the jet cross-section downstream, indicating leaner mixtures with Φ~1
  - Little/no soot is found in the jet, consistent with fuel-lean mixtures
  - Formaldehyde formed during ignition persists late in the cycle, especially near the injector, and exhaust UHC emissions are high
  - Chemical kinetics modeling predicts regions near injector with long-lived formaldehyde are lean, and incomplete combustion can yield UHC and CO emissions