A Conceptual Model for Partially Premixed Low-Temperature Diesel Combustion Based on In-Cylinder Laser Diagnostics and Chemical Kinetics Modeling

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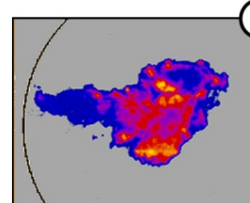
Program Manager: **Gurpreet Singh**

Sandia's diesel conceptual model describes mixing, combustion up to end of injection

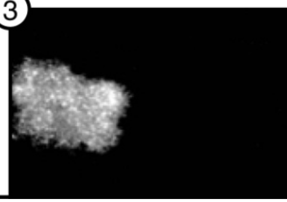
O_2 = 21% (no EGR)
SOI = 10 BTDC
P_{inj} = 1000 Bar

4 — PAH PLIF: Soot Precursors
As hot ignition reactions increase the temperature in the jet, fuel fragments are formed into chemical building blocks for soot.

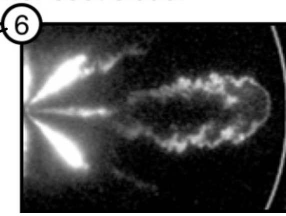
5 — LII: Soot Concentration
Shortly after the premixed fuel burns, soot is formed in the hot, fuel-rich region throughout the jet cross-section.



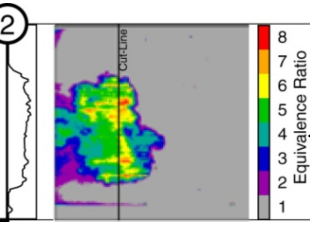
3 — Chemiluminescence: Ignition
Spontaneous ignition reactions occur in the hot mixture of fuel and air throughout the leading portions of the jet.

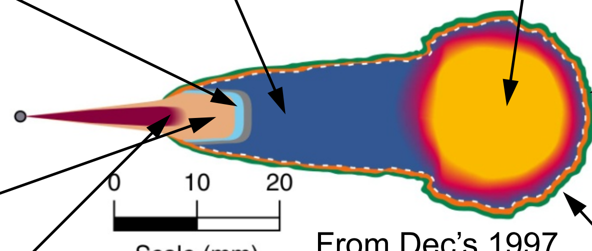


6 — OH PLIF: Diffusion Flame
Shortly after the premixed fuel burns, a thin diffusion flame forms on the jet periphery, surrounding the interior soot cloud.



2 — Rayleigh Scatter: Vapor Fuel
The vaporized fuel-air mixture downstream of the liquid is relatively uniform and fuel-rich (Φ = 2-4).

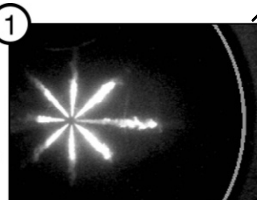


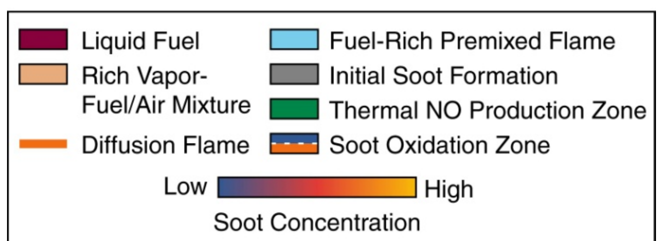


From Dec's 1997 conceptual model (SAE 970873).

7 — NO PLIF: Thermal NO
NO forms on the periphery of the jet in the hot diffusion-flame products.

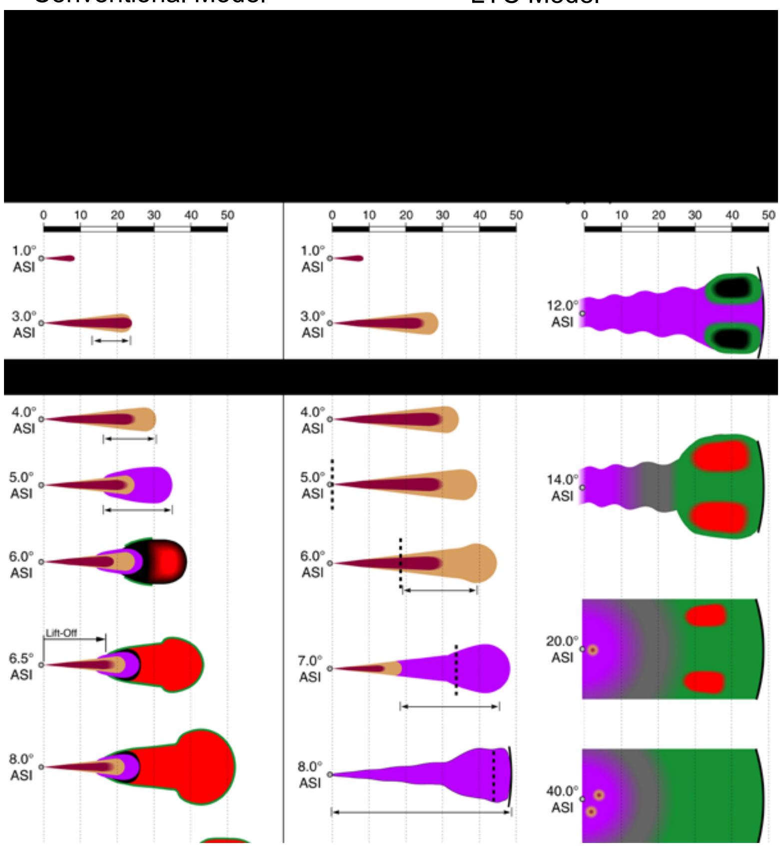
1 — Mie Scatter: Liquid Fuel
After penetrating approx. 25 mm, the hot, entrained gases completely vaporize the liquid fuel.





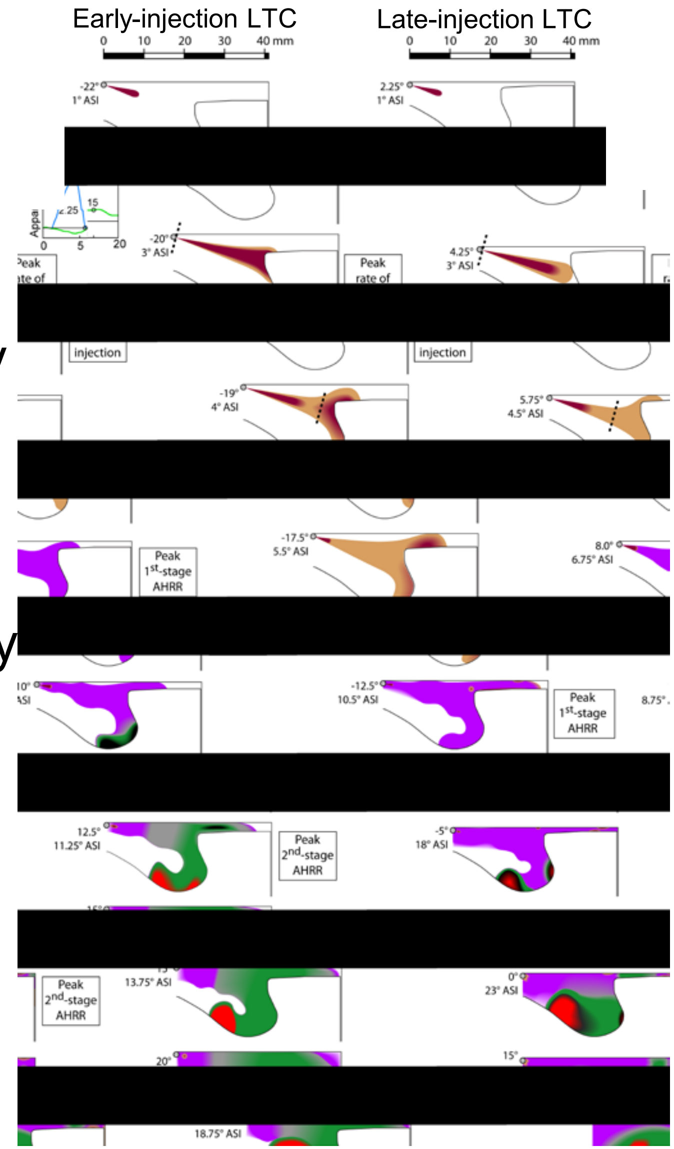
LTC conceptual model review article includes both heavy- and light-duty perspectives

- Team effort with Lyle Pickett and Paul Miles
- September 2012: LTC conceptual model review article accepted for journal publication in Progress in Energy and Combustion Science



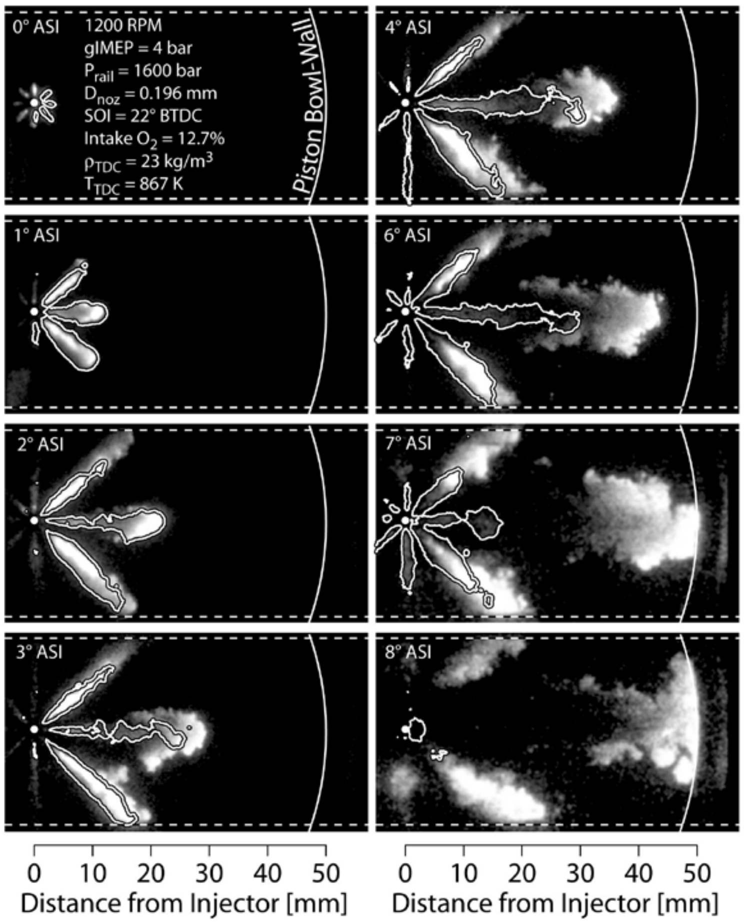
light-duty
→

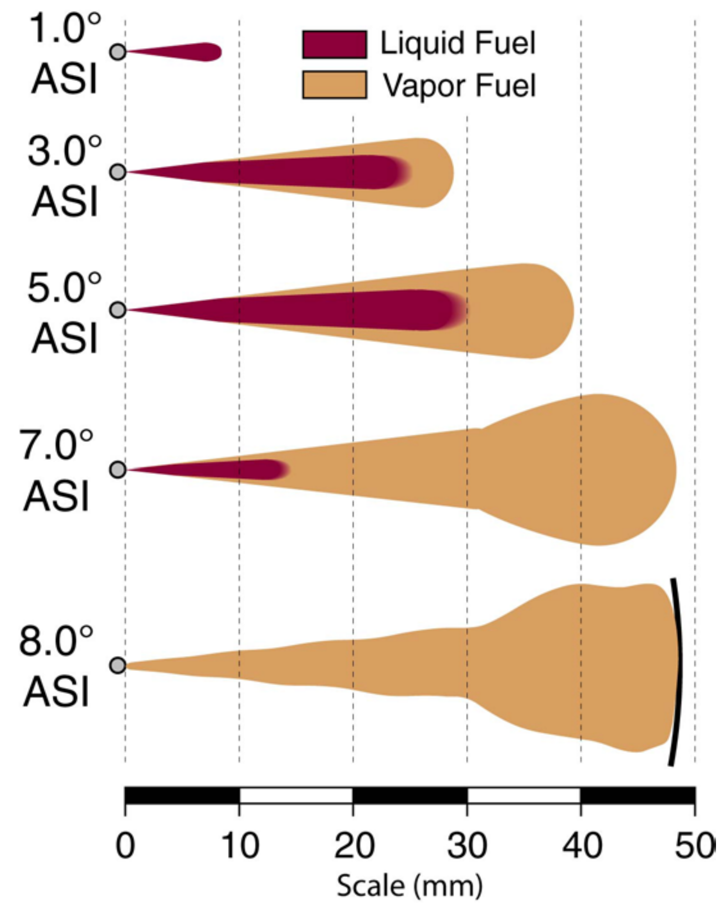
heavy-duty
←



LTC spray penetrates more quickly + longer liquid; liquid recedes after EOI, but before SOC

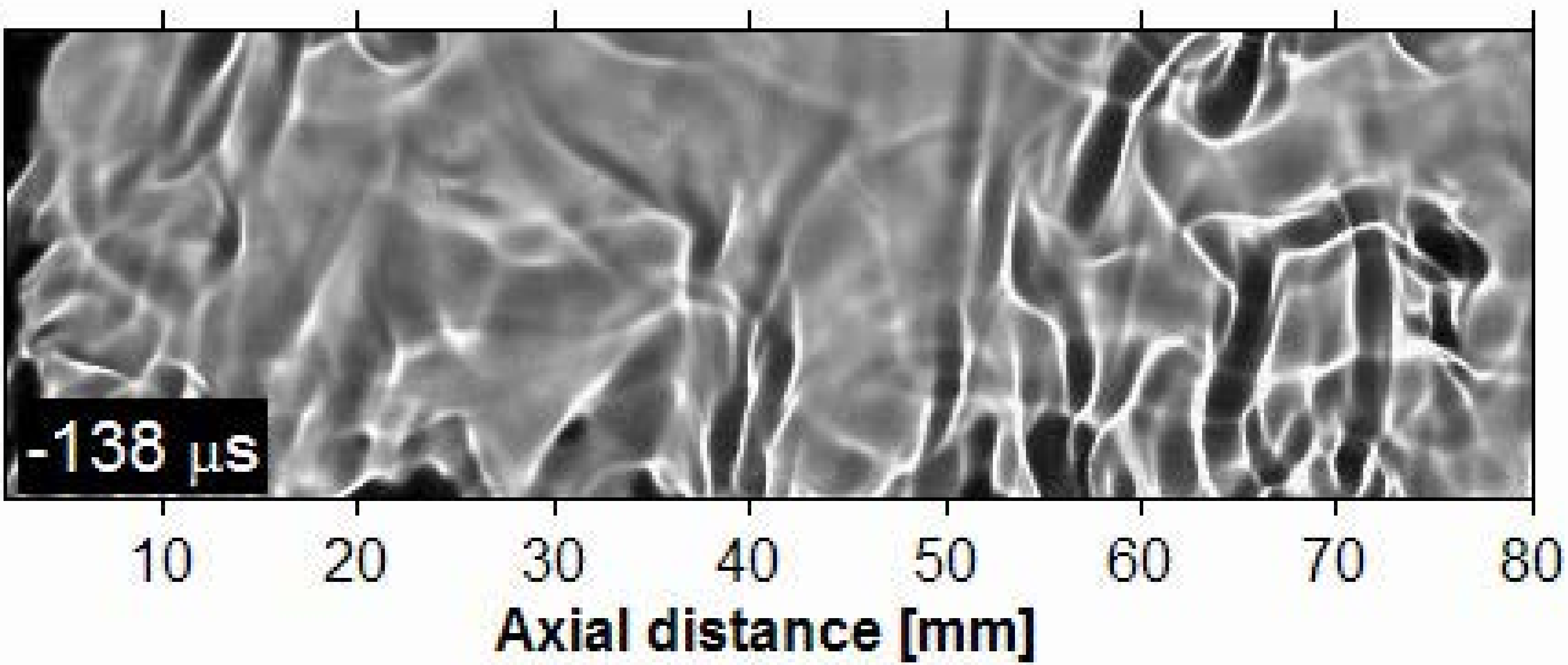
- Injection into lower density: faster spray penetration, longer liquid length
- Liquid recedes before SOC as vapor hits piston wall





Experiments show significant near-injector structural changes after EOI

- Upstream velocities decrease significantly after EOI, downstream velocities are higher
- Jet is tightly confined during injection, but large near-injector structures emerge after EOI



Diesel Shadowgraph (Lyle Pickett and coworkers, available at www.sandia.gov/ecn/)

LES air-jet model shows fluid-mechanical changes in jet structure and entrainment increase after EOI

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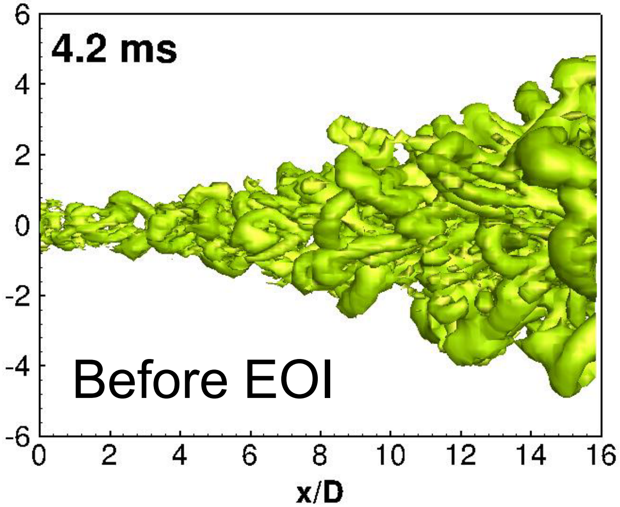
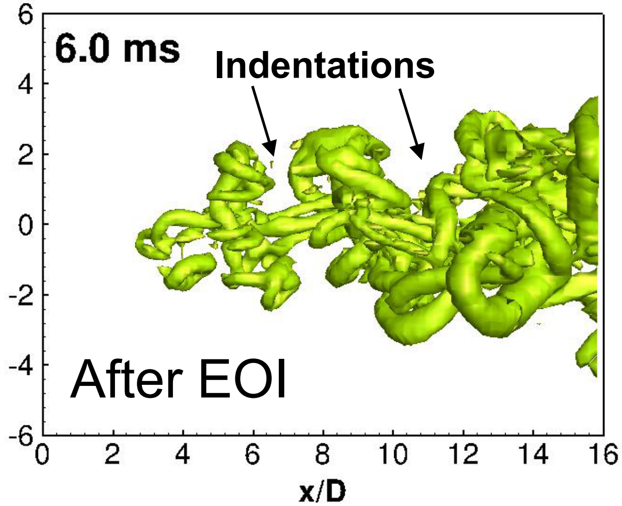
LES λ_2 visualization shows ambient engulfment between separating large-scale structures after EOI



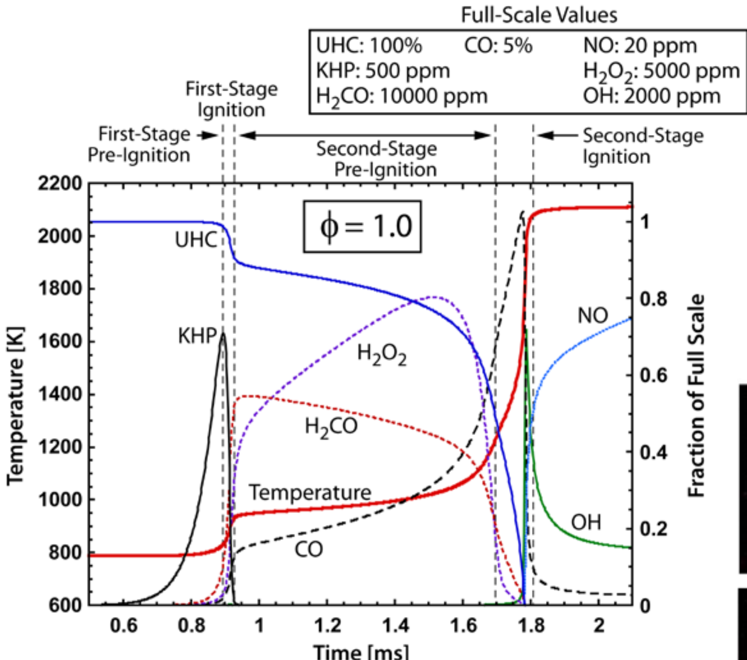


- $\lambda_2 \equiv 2^{nd}$-largest eigenvalue of $S^2 + \Omega^2$ (S and Ω $\equiv$ symmetric and anti-symmetric parts of ∇V)
- Vortex cores have $\lambda_2<0$, so $\lambda_2=0$ marks vortex core boundary, where azimuthal velocity is max.
- After EOI, vorticity breakdown and turnover rates decrease, so large structures grow
- Axial velocity inversion separates large structures, inhibiting coalescence
- Ambient fluid entrains into indentations between large structures (not apparent in RANS)
- Small-scale dynamics (scalar dissipation) decrease: not responsible for more entrainment

LES predictions imply that boundary conditions (rate-shaping), which affect large-scale structures can be tailored to achieve a desired mixing state

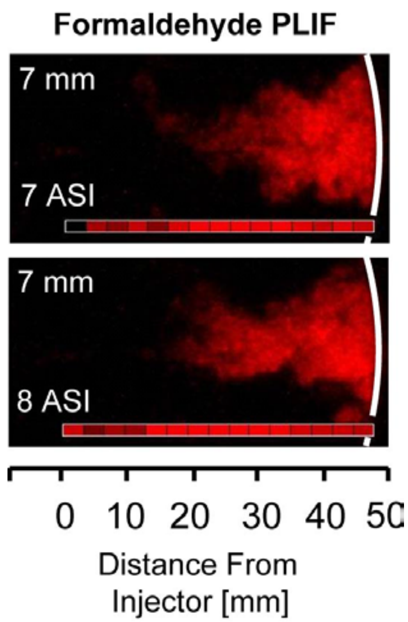
First-stage ignition in downstream vapor fuel, partially burned fuel (UHC, CO) throughout jet

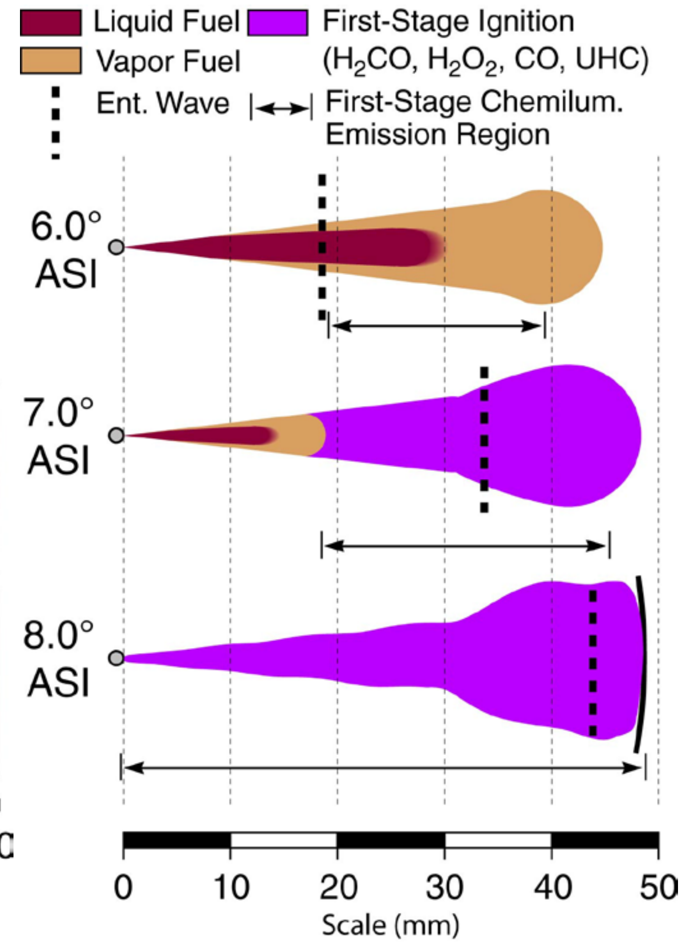
- LLNL chemical kinetics model: formaldehyde at 1st-stage ignition
- Experiments: Formaldehyde fluorescence at 1st stage, throughout jet



← Model
Proc. Comb. Inst. 31 (2007) 2921–2929

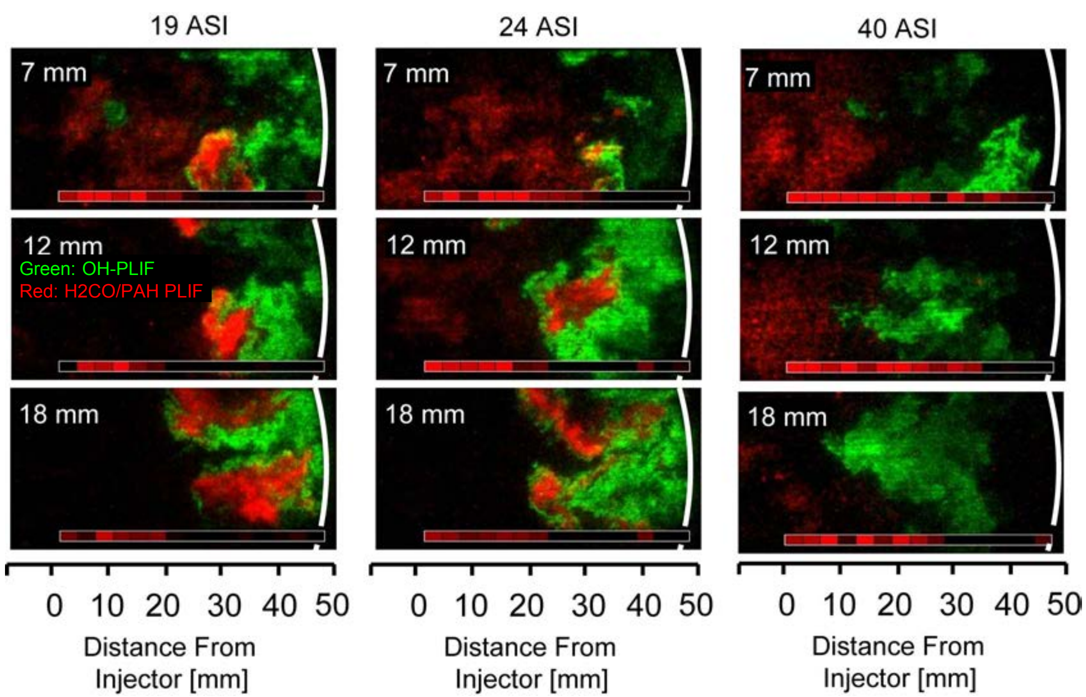
Experiment →

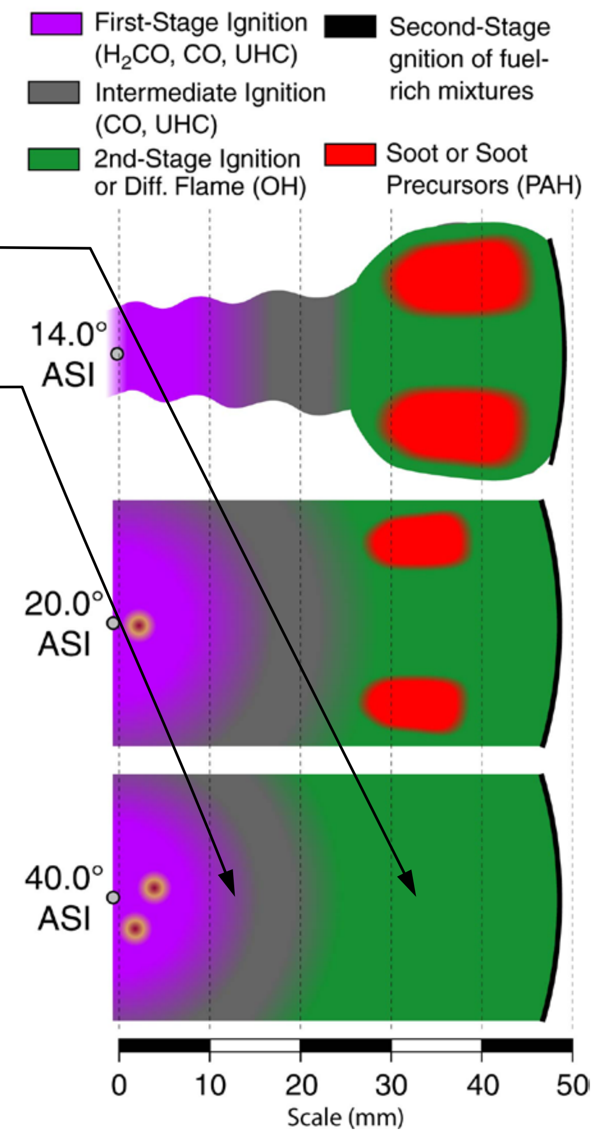




Late cycle: soot pockets largely oxidize, formaldehyde, CO, UHC remain upstream

- Late in cycle, simultaneous PLIF of OH (green) and formaldehyde/PAH/soot LII (red) show soot pockets surrounded OH
- Soot pockets are mostly oxidized by 40º ASI
- Partially burned fuel (CO, UHC, formaldehyde) remain late in cycle





Experiments show over-lean regions near injector, where kinetics models predict partial combustion

- Experiments: vapor-fuel tracer-PLIF shows lean mixtures near injector where combustion-PLIF shows late-cycle formaldehyde and CO
- LLNL kinetics models: Lean mixtures have long dwell between first- and second-stage ignition, with UHC and CO persisting to exhaust

Kinetics Model
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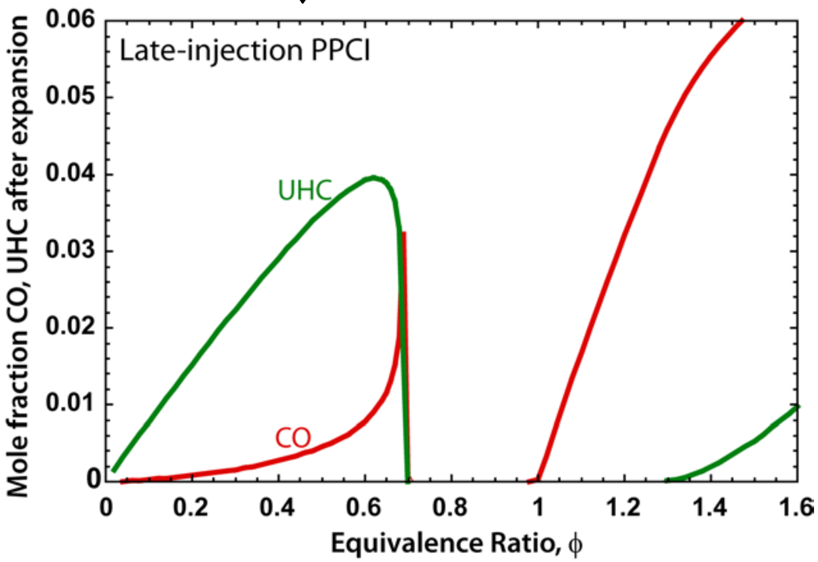
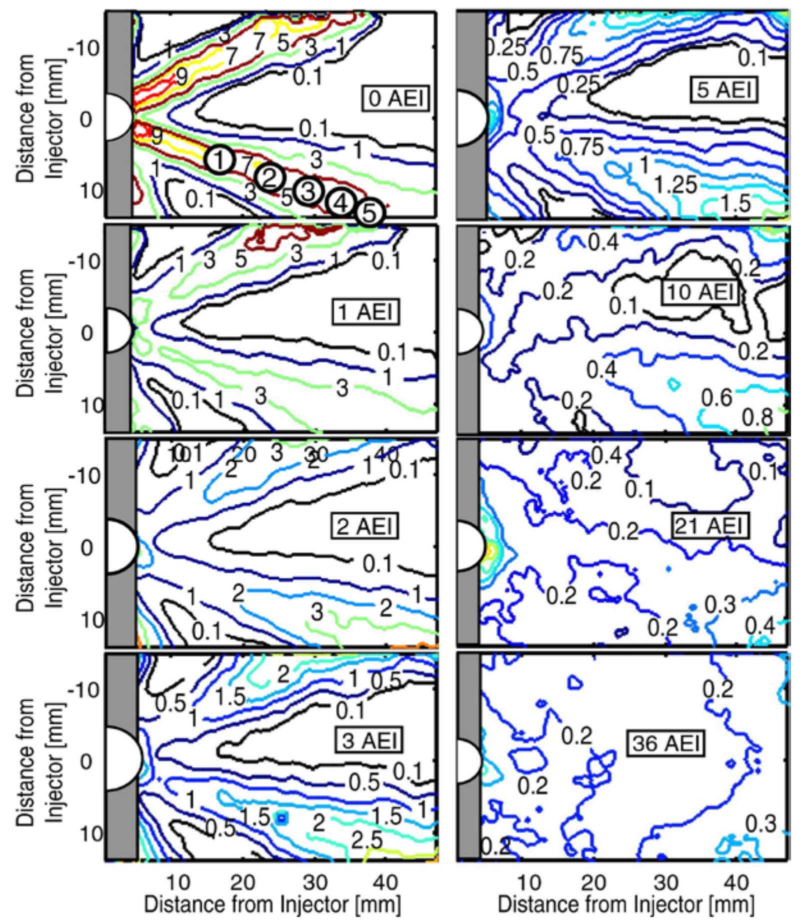
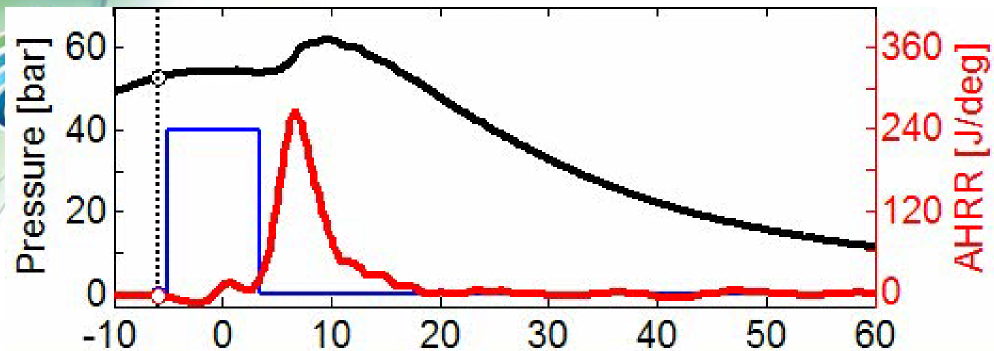
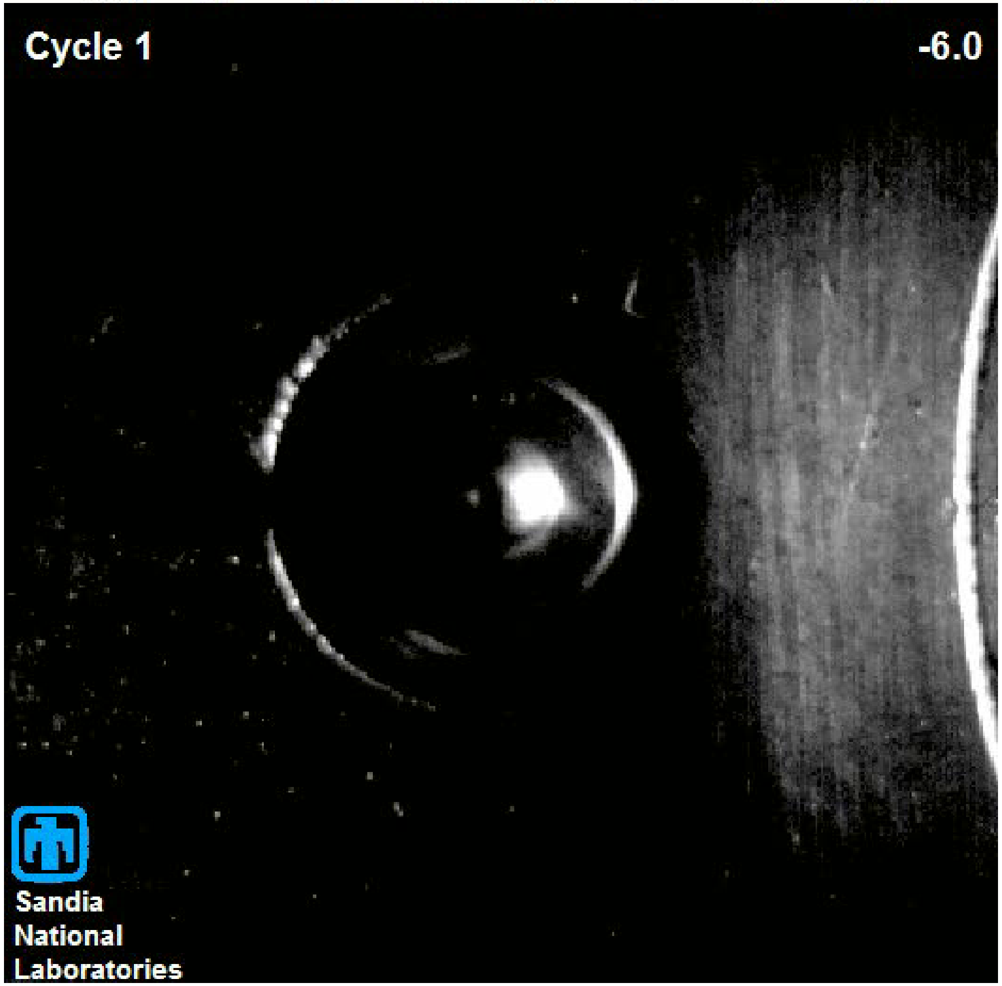


ϕ from experiment →



LTC PCCI: Injector Dribble



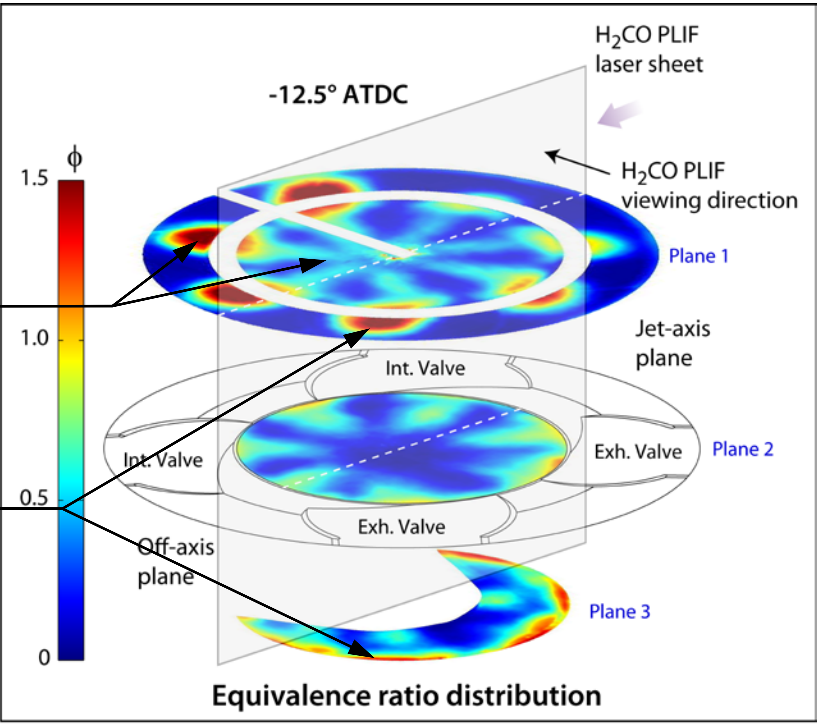


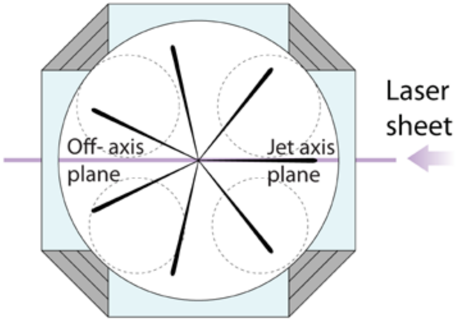
- Diesel PRF (realistic boiling pt)
- Droplets emerge from different holes each cycle
- "Sparkling" could be flash-boiling events or tumbling ligaments

Fuel	Diesel PRF CN42.5
Intake	13% O_2
Load	3 bar IMEP
Intake T	78 C
Intake P	2.14 bar
CR SOI	-5° ATDC
Speed	1200 rpm
Engine r_C	10.75
View	35 mm square
Framing	14400 fps
Filter	None

Light Duty: Swirl transports mixtures away from jet axes, first-stage ignition throughout jet

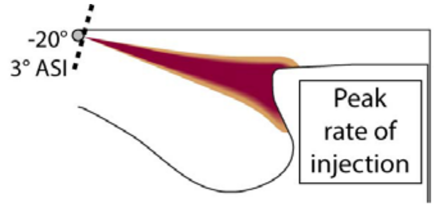
- For light-duty, swirl transports mixtures off the jet axes
- Like heavy-duty, light-duty jet is lean upstream and fuel-rich close to bowl
- Piston bowl contour redirects jet, with rich mixtures into squish and piston bowl
- First-stage ignition (H_2CO PLIF) occurs nearly simultaneously throughout jet





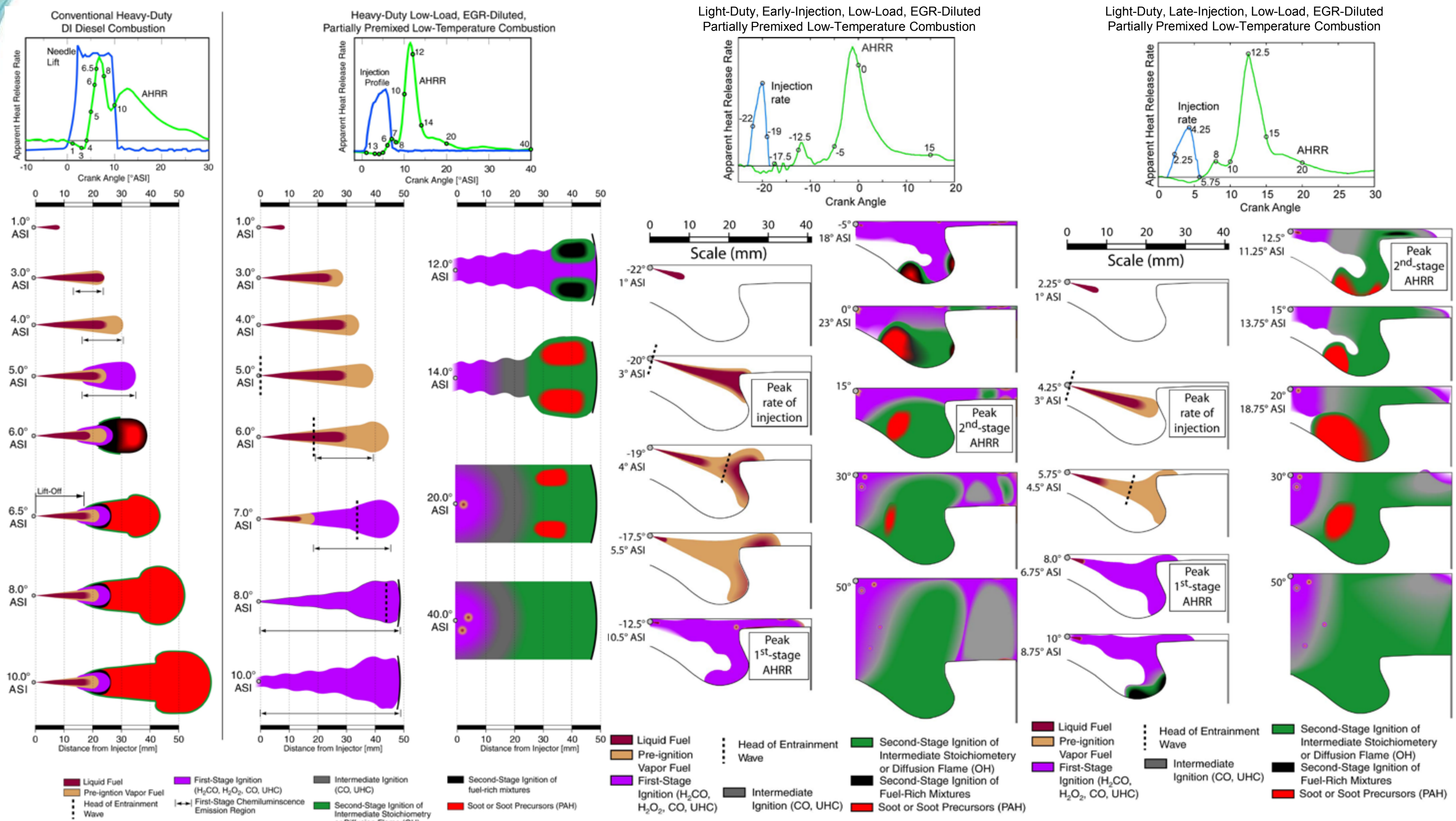
Light Duty: Interaction with piston bowl and reverse squish play more prominent role

- In light-duty engines, liquid fuel impinges on piston, especially for early injection
- Jet is split by lip of piston bowl, with rich mixtures mostly in bowl
- Reverse-squish pulls lean near-injector mixtures into squish: incomplete combustion + late film vaporization → CO, UHC

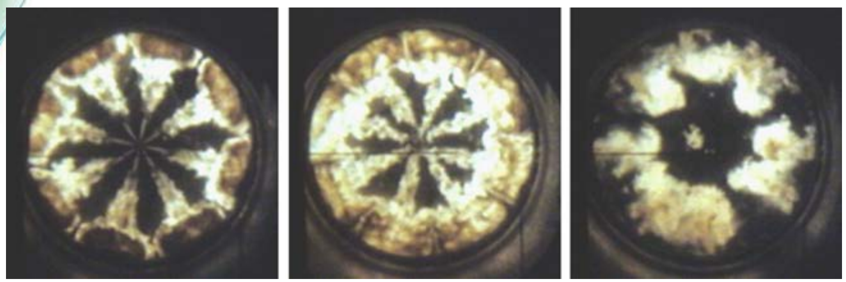


Review article summarizes heavy- and light-duty low-load EGR-diluted partially premixed LTC

"Conceptual models for partially premixed low-temperature diesel combustion," Mark P.B. Musculus, Paul C. Miles, and Lyle M. Pickett, Progress in Energy and Combustion Science, 2012 (accepted)

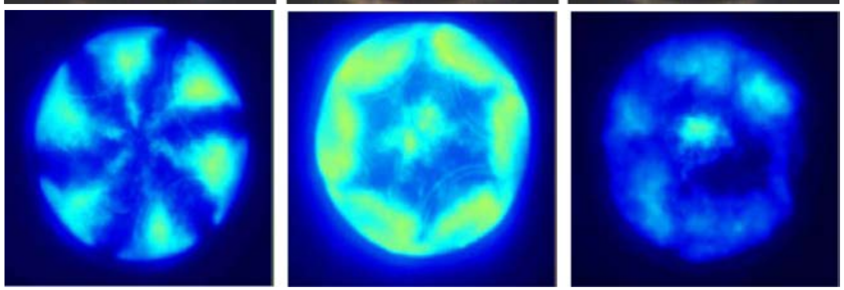


Injector dribble is not universal in the literature, but it is not uncommon either



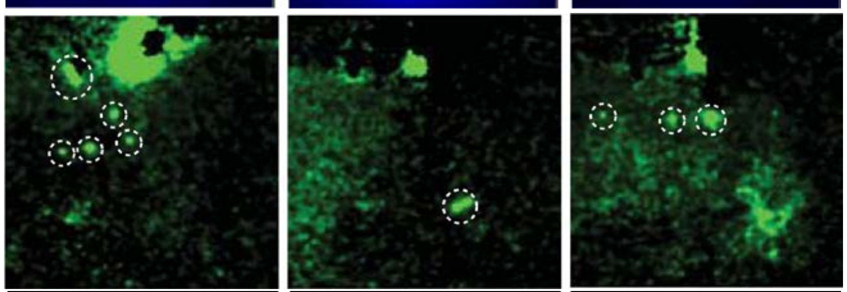
SAE 930971 (Dec, Sandia)

- Heavy-duty, diesel reference fuel
- Cam-driven, mini-sac injector
- Late soot at center



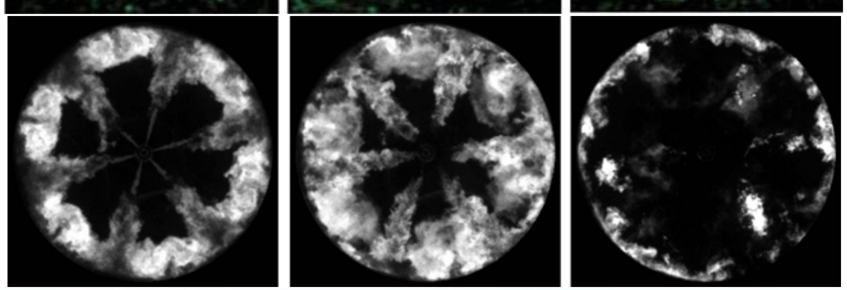
SAE 2005-01-3845 (Taschek et al., Aachen)

- Light-duty, diesel fuel
- Common-rail, mini-sac injector
- Conceptual model: Inj. sac vapor → soot



SAE 2009-01-1446 (Ekoto et al., Sandia)

- Light-duty, diesel fuel
- Common-rail, mini-sac injector
- Side-view PLIF, bright fuel droplets late



SAE 2001-01-2004 (Mueller et al., Sandia)

- Heavy-duty, diesel reference fuel
- HEUI, VCO injector
- No late soot at center (but sometimes yes)