SAND2016-4300PE

Optical Investigations of Multiple Injection Strategies in a Light-Duty Optical Diesel Engine

Daimler site visit

Dr.-Ing. Stephen Busch, Dr. Kan Zha
May 12, 2016
Sandia National Laboratories

Portions of this work were performed in collaboration with General Motors

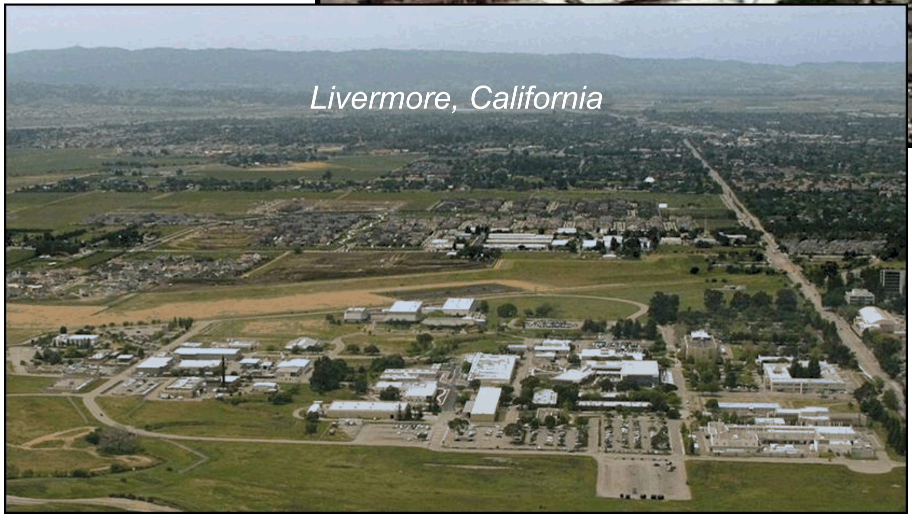
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

Outline

- Introduction
  - Sandia National Laboratories (Livermore, California)
  - Engine Combustion Research Program
- Investigations of close-coupled pilot injections
  - Combustion noise reduction
  - Injection dynamics
  - Combustion noise reduction mechanism
- Ongoing work
  - Ignition processes in main mixture with pilot injections
  - Stepped-lip piston bowls: understanding late-cycle behavior
- Discussion

Sandia National Laboratories

- "Exceptional service in the national interest"
- Largest national lab
  - ~10,000 employees
  - ~$2.2 B/yr
- Missions
  - Nuclear weapons engineering
  - Defense systems
  - Homeland security
  - Energy
- Locations
  - Albuquerque
  - Livermore
  - Also Nevada, Hawaii, DC



Engine Combustion Research Program

- Mission: Provide the combustion and emission knowledge-base needed by industry to develop high-efficiency, clean engines adapted to future fuels
  - Focus on needs from 5 to 20 years out
- Primary sponsor is DOE Office of Vehicle Technologies (VT)
  - Program managers: Gurpreet Singh, Leo Breton and Kevin Stork
- Supports VT engine and fuels program goals
  - Greatly improved fuel efficiency (10% to 40% by 2030)
  - Emissions compliant (Tier 3, Euro 5/6 particulate number)
  - Fuel effects on conventional & advanced engine combustion
- Strong collaborations with industry, universities, and other national labs (since the start in the mid-70s)

Engine Combustion Research Program (cont.)

- Program research directions are aligned with DOE/industry, USDRIVE, and 21st Century Truck (21CTP) roadmaps
  - Detailed research directions are modified annually in response to roadmap updates, VTO input, discussions with industry in various forums:
    - Frequent PI to PI interchanges with partners
    - DOE VTO Annual Merit Review
    - New EERE mandated reviews of future research plans
    - Advanced Engine Combustion MOU
- Additional sponsors - complementary, precompetitive research: Caterpillar, Toyota, Chevron, the Spray Combustion Consortium and internal funding (LDRD) ~ 20%
- >30 staff, technologists, post docs, and visiting researchers
  - Staff deeply engaged in leadership roles in the field
  - 5 SAE Fellows

Our DOE research is conducted under the AEC MOU led/managed by Sandia

USDRIVE

21ST CENTURY TRUCK PARTNERSHIP

Ford, GM, Volvo, Cummins, bp, Shell Global Solutions, ExxonMobil, Chrysler, GE, PACCAR Inc, Lawrence Livermore National Laboratory, Chevron, Caterpillar, Electro-Motive, Oak Ridge National Laboratory (Managed by UT-Battelle for the Department of Energy), International, Sandia National Laboratories, Argonne National Laboratory, Detroit Diesel, John Deere, NREL National Renewable Energy Laboratory (Innovation for Our Energy Future), Los Alamos National Laboratory

DOE/NSF funded universities:

U Wisconsin
Stanford
UC Berkeley
MIT
Michigan State
Michigan Tech
Clemson
Yale
New Hampshire
U Vermont
Penn State
U Connecticut
Wayne State

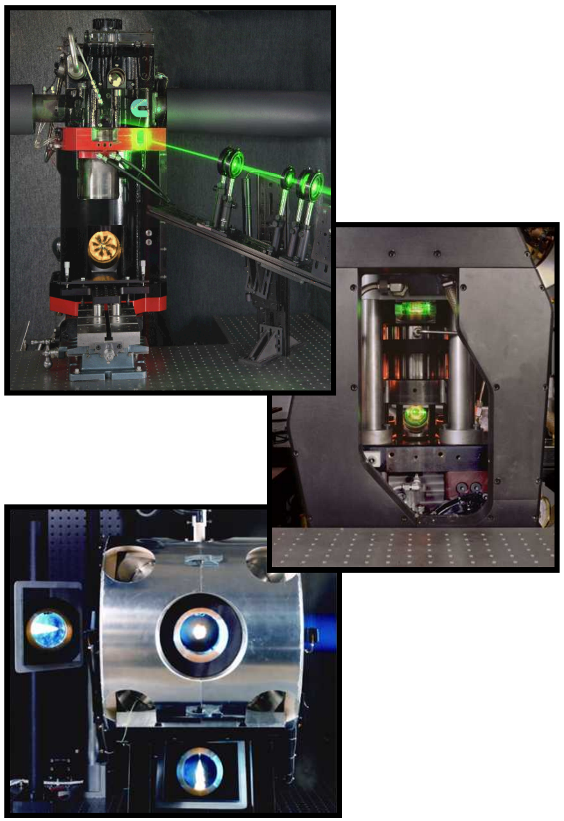
Research ⇒ Products

MOU in force through 2018

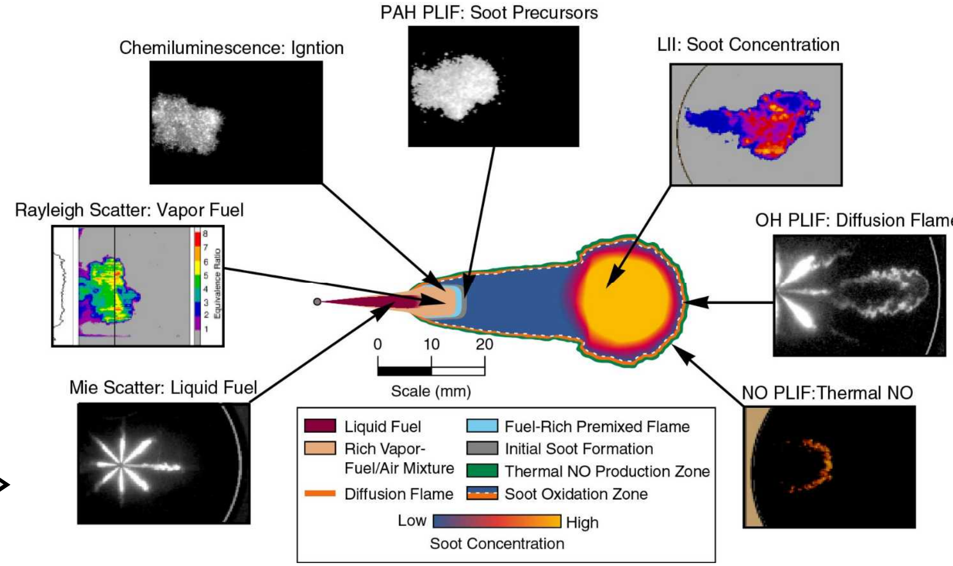
Next AEC Program Review: 8/16-19, 2016 at USCAR

Impact – We provide data & understanding to:
(a) guide engine design
(b) advance computational design tools

Optical engine platforms
&
Laser diagnostics

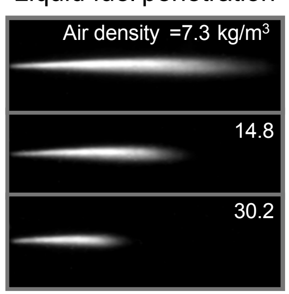


Diesel combustion:

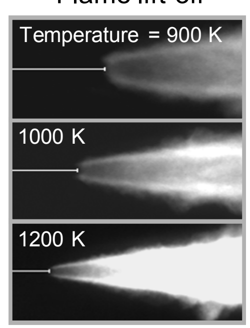


Scaling of critical processes

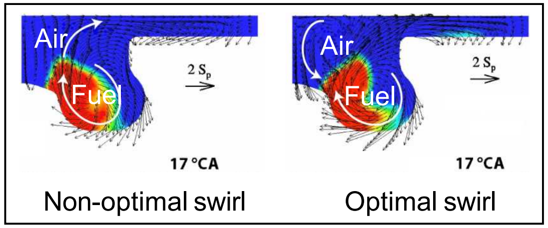
Liquid fuel penetration



Flame lift-off



In-cylinder flow



Investigations of multiple injection strategies in a light-duty, swirl supported Diesel engine

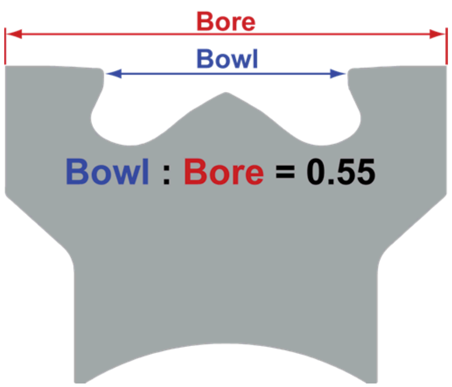
- Multiple injection strategies are commonly used to control combustion noise and reduce pollutant emissions
- A detailed understanding of how multiple injections impact mixture formation, ignition, combustion, and pollutant formation is lacking
- Focus of recent light-duty research: close-coupled pilot injections and the impact of pilot-main dwell on:
  - Combustion noise
  - Injector dynamics
  - High temperature ignition processes in the main mixture
  - Late-cycle flow behavior

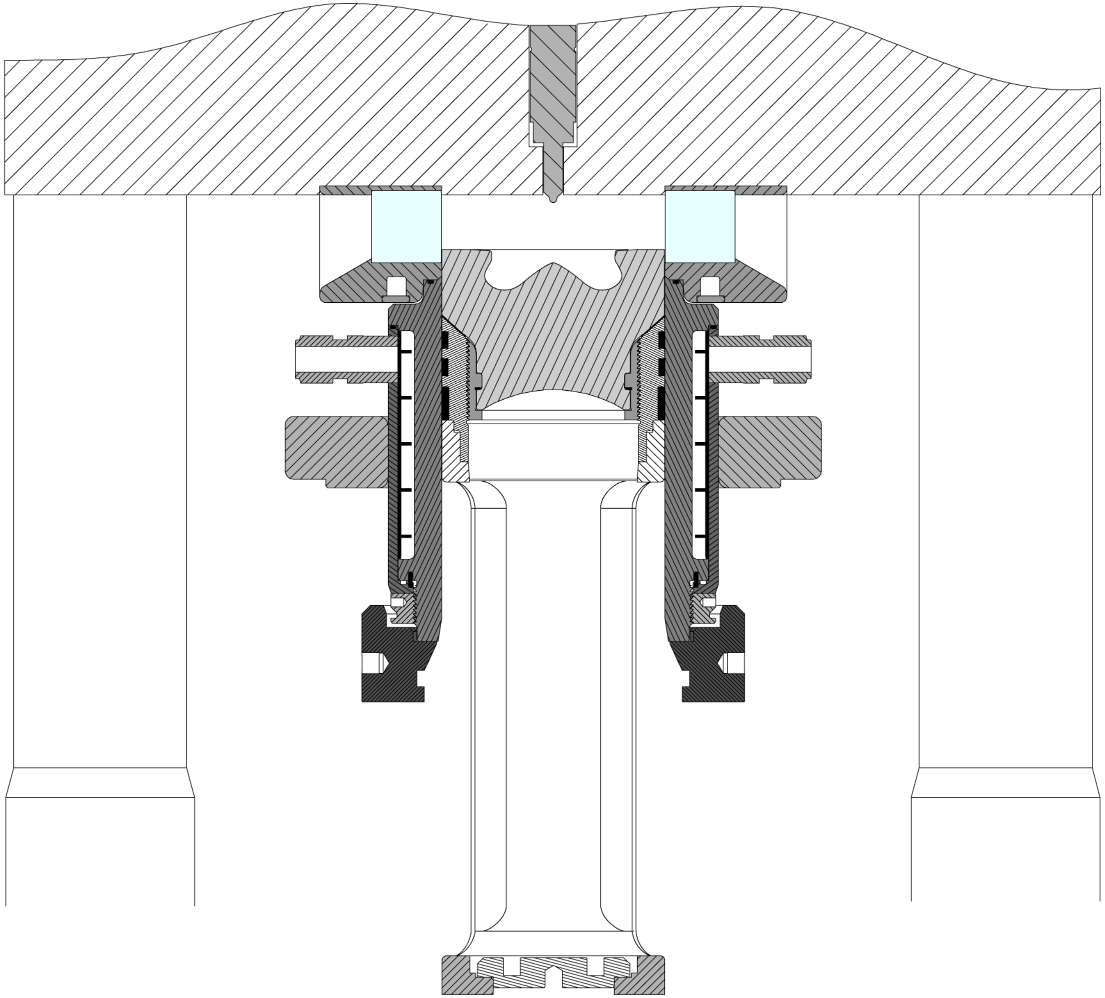
Experimental setup: engine configuration

Single-cylinder engine data

Bore x Stroke	82 mm x 90.4 mm
Compression ratio	16.7:1
Valves	4
Injector	Fast-acting solenoid valve
Holes x Ø	7 x 139 µm
ks	1.5 / 86
Included angle	149°

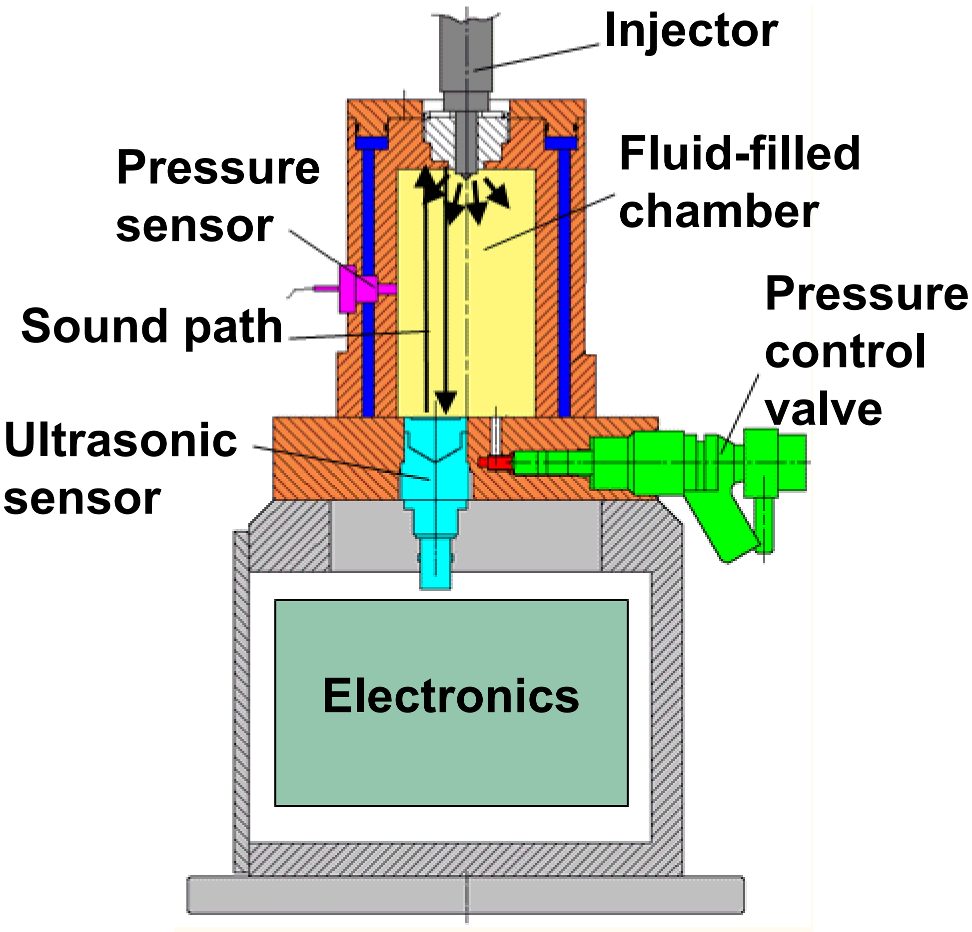
Bowl : bore ratio





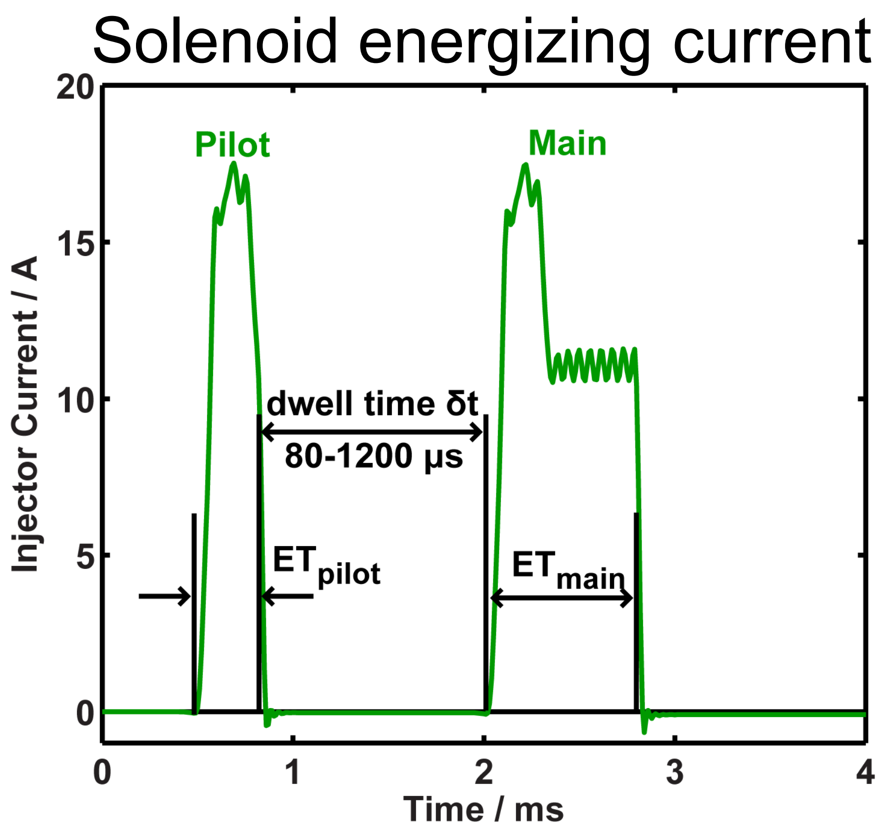
Experimental setup: injection rate measurements with the Moehwald HDA

- Same injection hardware as used in engine testing
- Same injection trains as used in engine testing
- Chamber pressure corresponds to cylinder pressure at time of injection
- Measurement of chamber pressure and speed of sound of fuel in chamber
  - Fuel density and compressibility effects taken into account
- Derived injection rates for each injection train



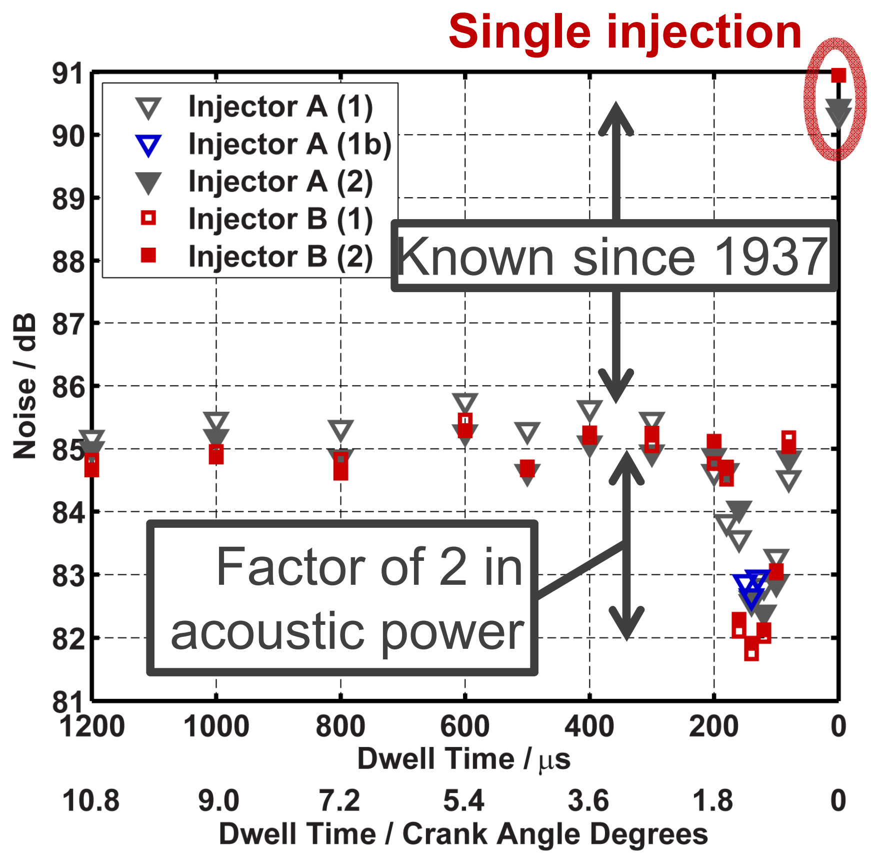
Experiments: pilot-main injection strategy

- Operating point:
  - Engine speed: 1500 rpm
  - Pilot injection mass: 1.5 mg
  - IMEPg: 9 bar
  - Injection pressure: 800 bar
  - 50% mass fraction burned: 13 deg. after TDC
  - Fuel: DPRF58 (58 vol% heptamethylnonane, 42 vol% n-hexadecane)
- Vary energizing dwell between pilot and main injection
  - 1200 – 80 µs (10.8 – 0.7 crank angle degrees)



Trend in combustion noise with changing pilot-main dwell

- Combustion noise is computed based on the measured cylinder pressure
- Adding a pilot reduces noise, but a further reduction is possible at a dwell of 140 µs
- What is the mechanism responsible for this combustion noise reduction?

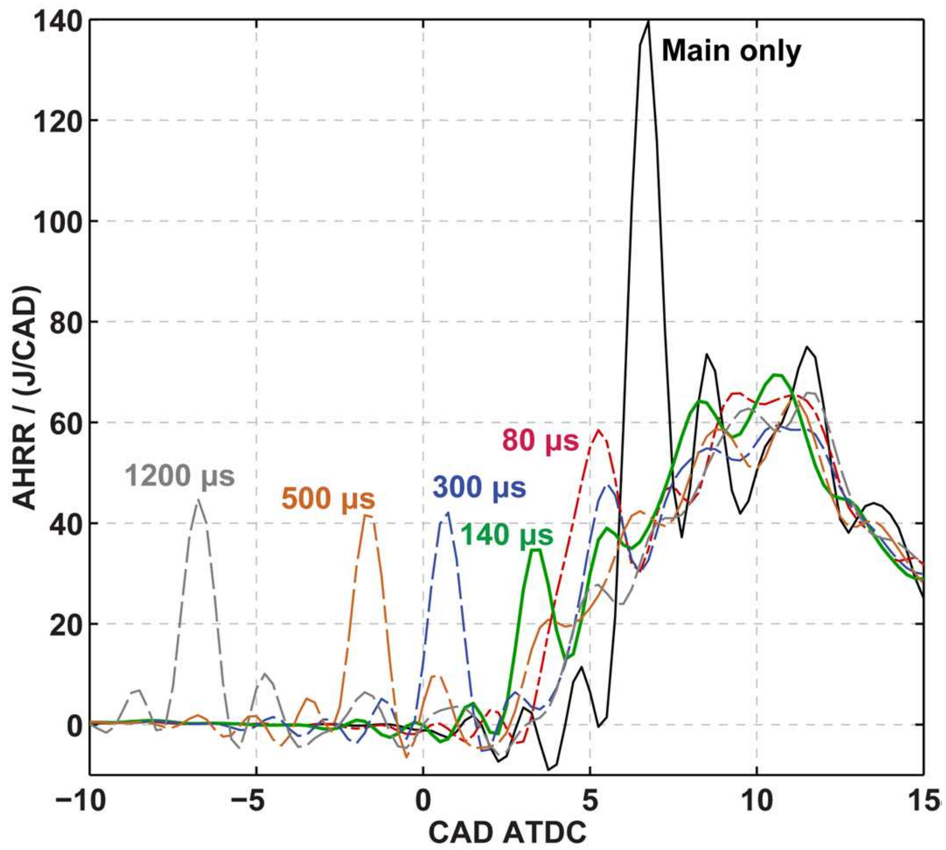


Reduction of noise by pilot injections reported in:
Jâfar, D., *Pilot Injection*, in *Engineering Magazine*. Office for Publication and Advertisements, Oct. 15, 1937: London.

Combustion noise calculated according to:
Shahlari, A., Hocking, C., Kurtz, E., and Ghandhi, J., "Comparison of Compression Ignition Engine Noise Metrics in Low-Temperature Combustion Regimes," SAE Int. J. Engines 6(1):541-552, 2013, doi:10.4271/2013-01-1659.

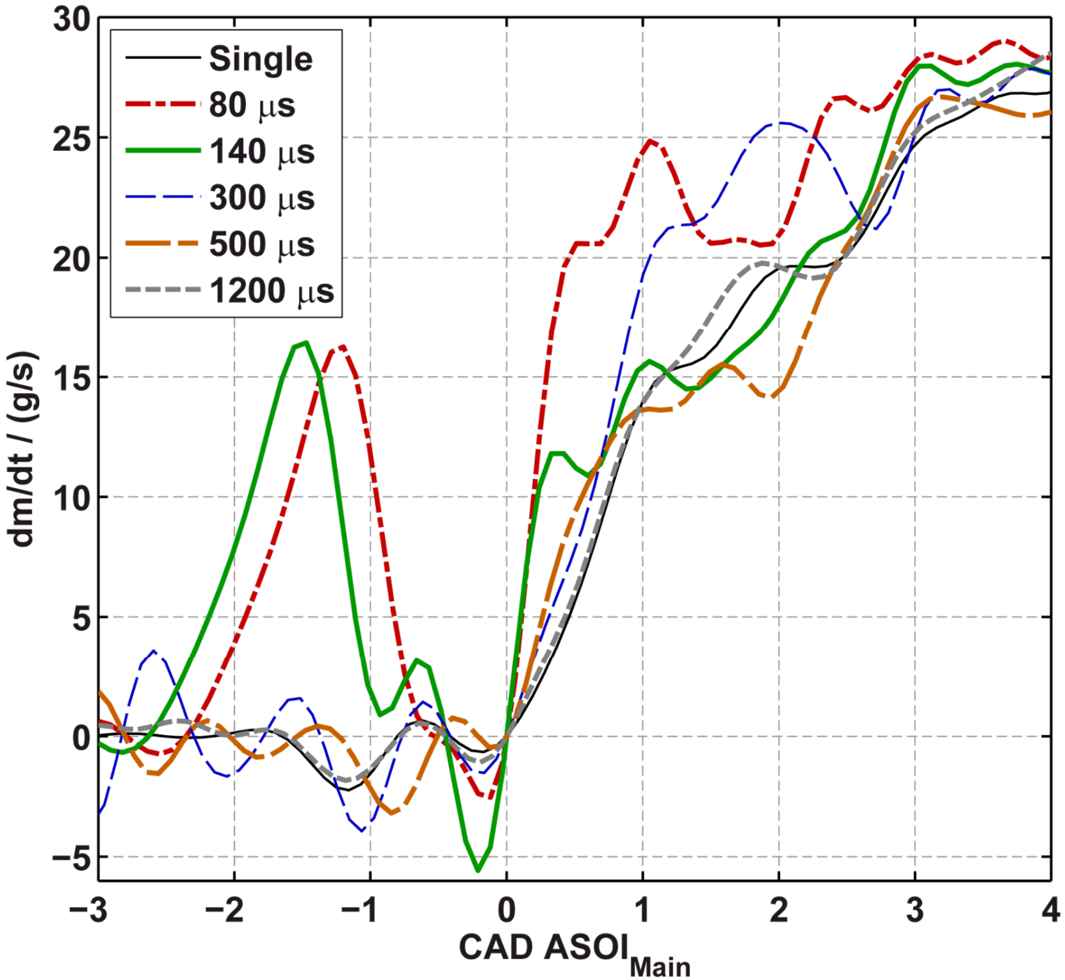
Pilot-main dwell: impact on apparent heat release profile

- Main injection only: clear premixed peak; mixing controlled combustion
- 1200 µs (far pilot): significantly reduced premixing as expected
- 500 µs and 300 µs: slight decrease in peak pilot AHRR; no significant change to main heat release
- 140 µs: peak pilot AHRR decreases; no significant change to main heat release
- 80 µs: no separation between pilot and main heat release events
- Does the pilot injection affect the main injection?



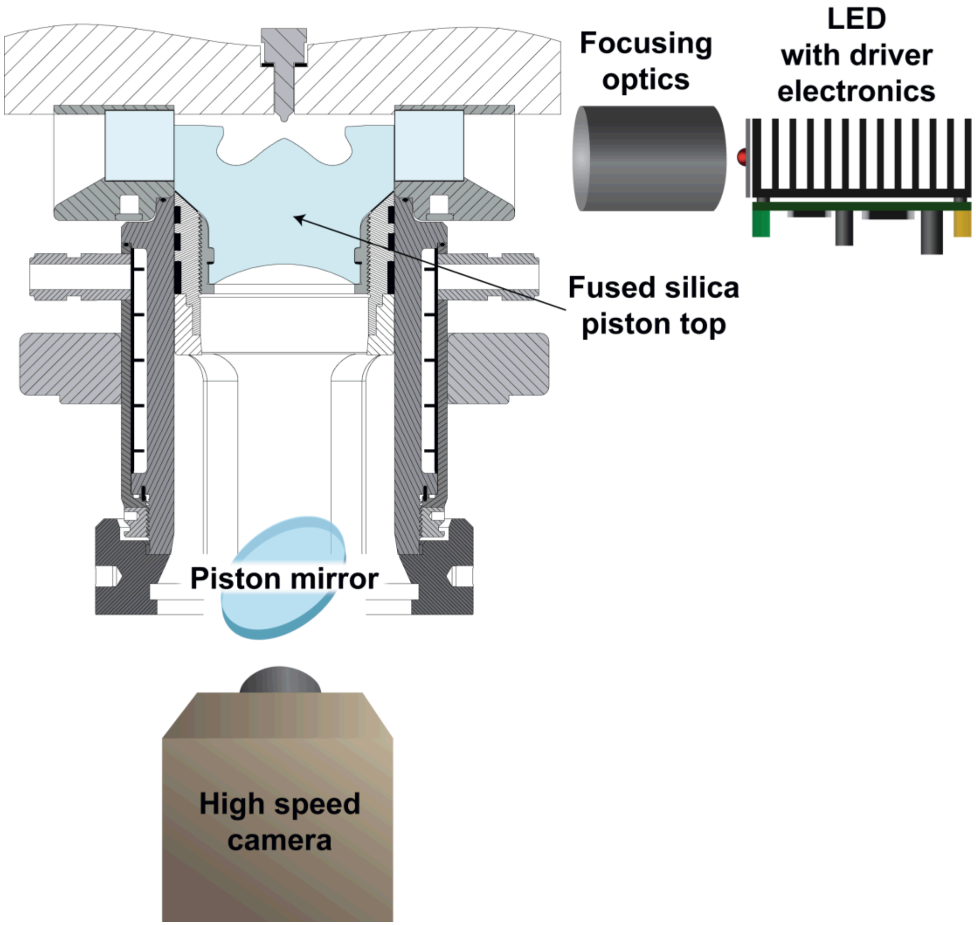
Measured fuel injection rates: Moehwald HDA

- Two injection events even for shortest dwells
- Changing dwell changes main injection rate shape
  - Dwell 1200 µs: main injection rate close to single injection rate
  - Dwell 80 µs: steepest injection rate increase
  - Dwell 140 µs: steep at first, less steep thereafter
- Does this rate shaping take place in the engine in this manner?



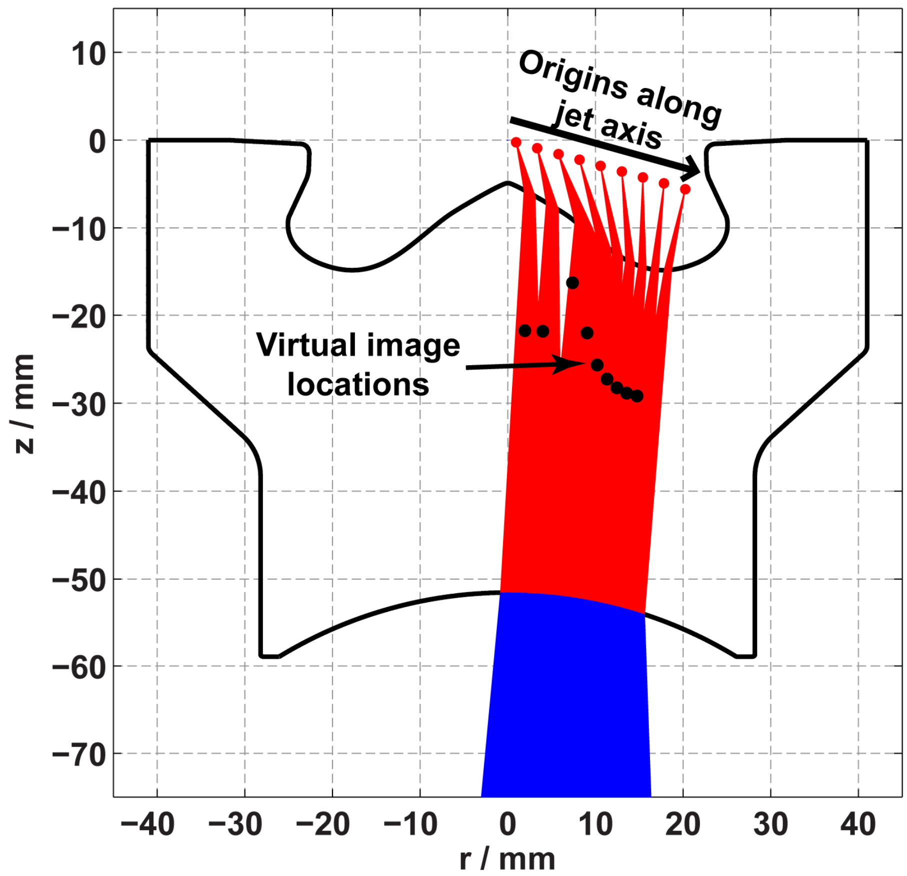
Experimental setup: high speed fuel injection imaging

- Operating conditions
  - Motored, air replaced with N_2
  - Comparable TDC density to fired operation
- Side illumination
  - High-energy pulsed LED
  - Non-uniform illumination (but better than illumination from below)
- Imaging through piston
  - Photron SA-X2 monochromatic CMOS
  - Enables view of injector tip
  - Imaging rate: 120 kHz
    - 0.075 CAD at 1500 rpm
  - Image size: 256x256 pixels



Automated image distortion correction with ray tracing

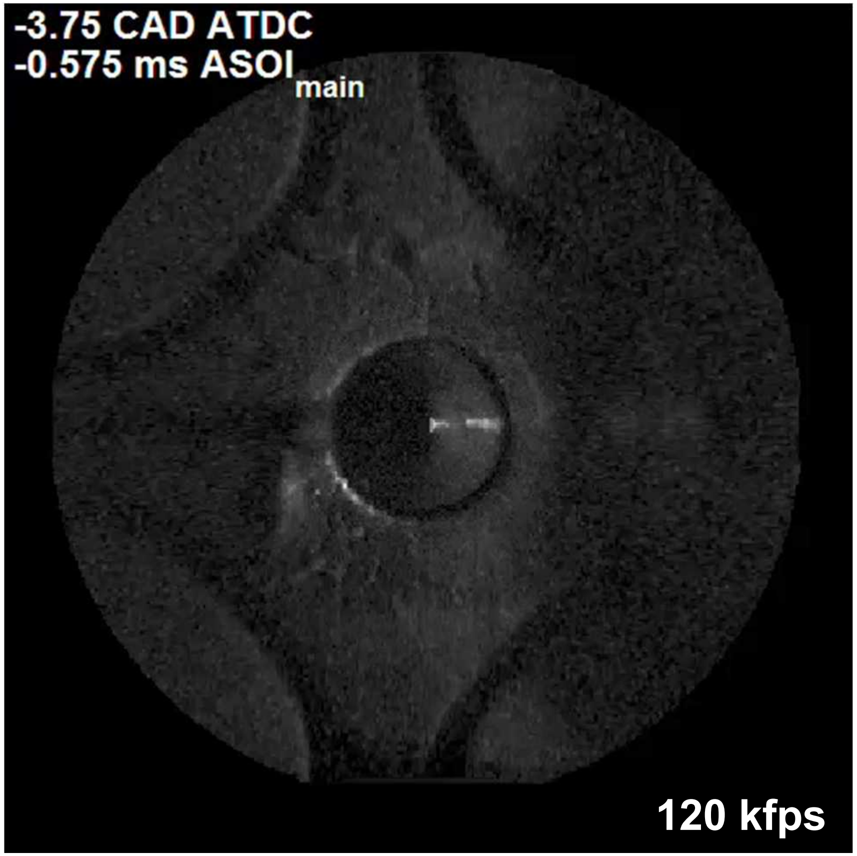
- Image distortion depends very strongly on the object's proximity to the piston
  - Particularly noticeable near pip
- De-warping to match a flat target image is not viable for imaging of fuel jets
  - Correction for one horizontal plane does not properly de-warp information from other planes
- De-warping performed along injector jet axis
  - Assume information comes only from this conical region of space
  - Final image resolution corresponds to 8 pixels per mm along jet axes



High speed Mie scattering imaging results

- Even at very short dwells, both the pilot and main injection events appear to be distinct
- Fuel dribble is observed after both injection events
- Does the penetration of liquid fuel correspond to the rate shaping trends measured with the HDA?

Single cycle; dwell 90 µs



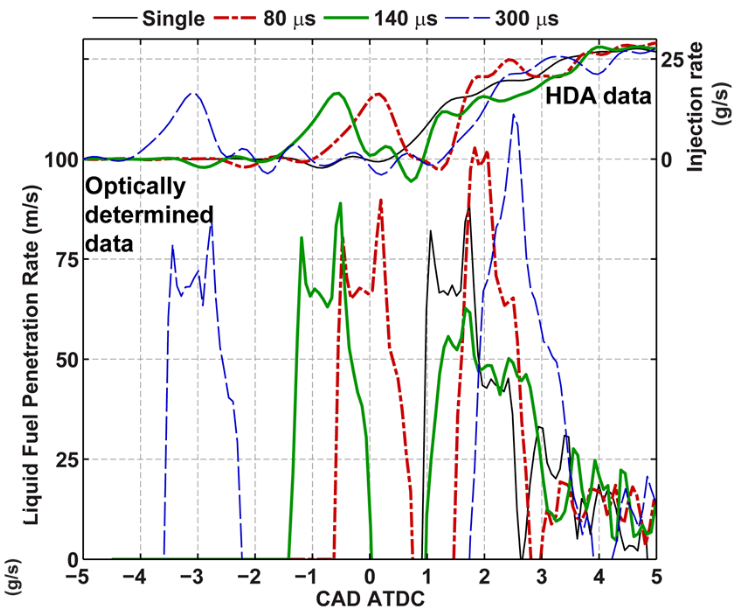
Images automatically distortion corrected

TA: Main injection rate shaping is affected by dwell with a close coupled pilot injection

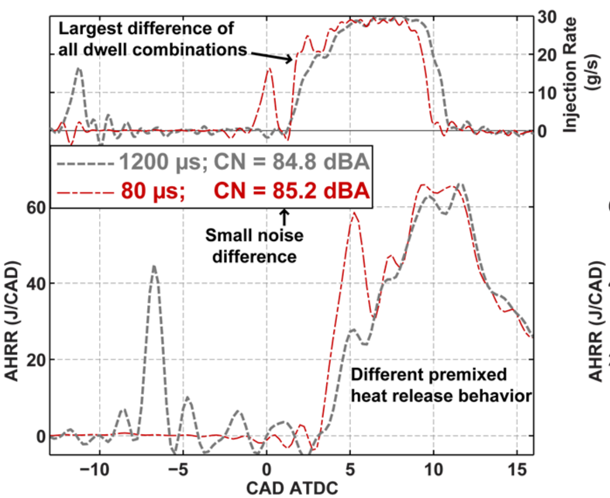
Main injection rate shaping does occur as dwell changes with a close-coupled pilot, but it is not responsible for the reduction in combustion noise.

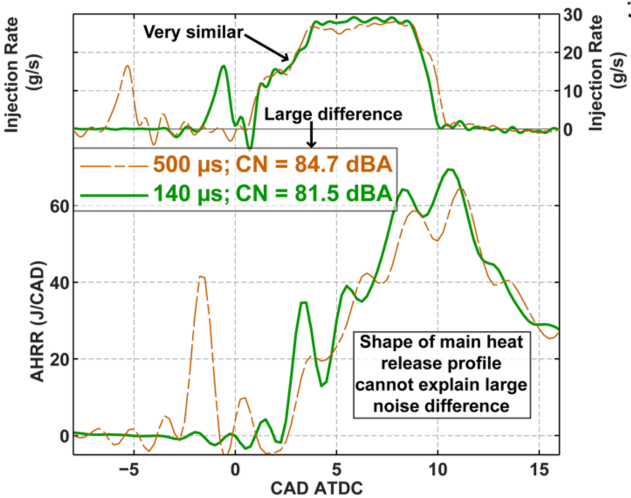
- **Injection rate measurements:** shape of main injection rise rate is affected by hydrodynamics in the injector & high pressure fuel line as dwell changes: top plot →

- **Optical engine measurements:** a similar trend in main injection rate shaping is observed in the engine with high speed imaging: bottom plot →



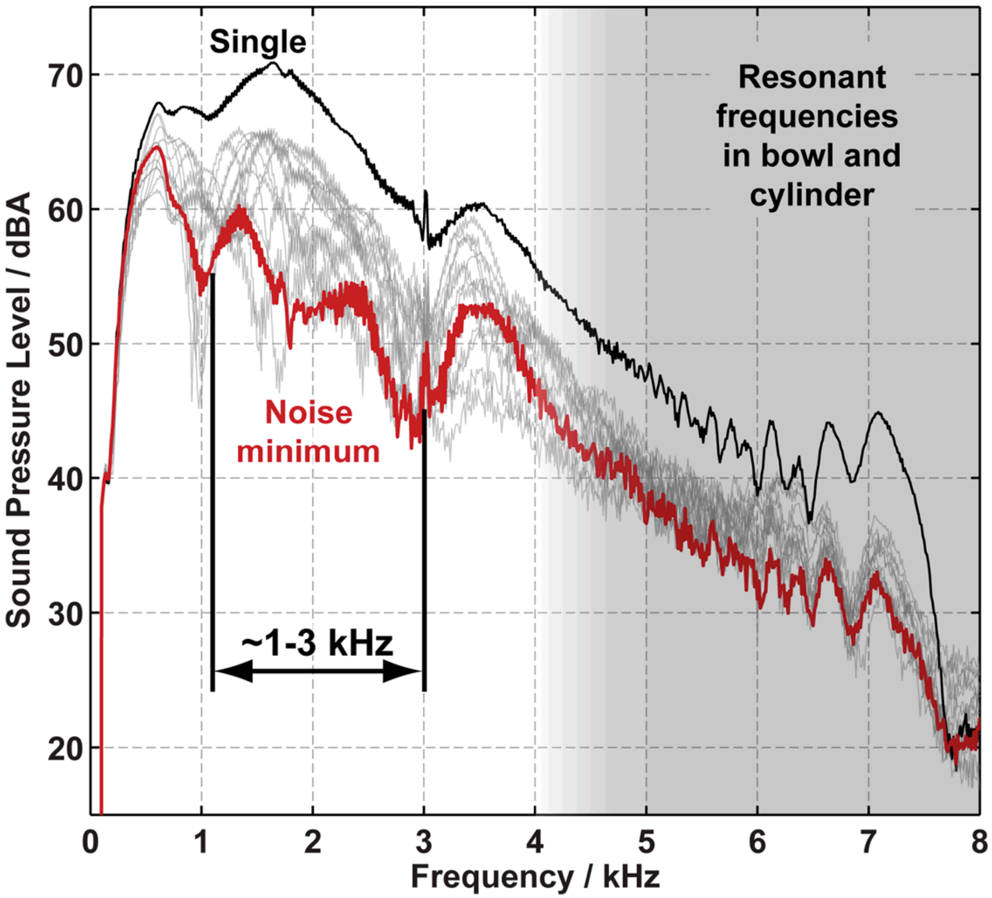
- **However:** main injection rate shaping trends do not correlate with noise trends





Frequency analysis reveals the spectral range associated with the noise reduction

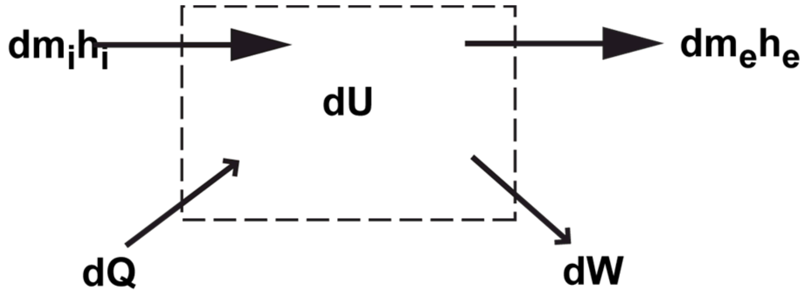
- Sound pressure level (SPL)
  - Shows each frequency's contribution to audible combustion noise
  - In this case, resonant frequencies contribute little to combustion noise
- Comparison of SPLs from all pilot-main dwells
  - Frequencies most strongly associated with the noise reduction: **~1-3 kHz**



A simple zero-dimensional thermodynamic model to predict combustion noise

- First law of thermodynamics

  $dU = dQ - dW + dm_i h_i - dm_e h_e$



- Idea gas law; continuity

  $PV = mRT; dm = dm_i - dm_e$

- Differential equations (solved using 4th order Runge-Kutta method):

$$dP = \frac{(\gamma - 1)dQ - \gamma PdV + (\gamma - 1)(dm_i h_i - dm_e h_e)}{V}$$

$$dT = \frac{PdV + VdP}{mR} - T\frac{dm}{m}$$

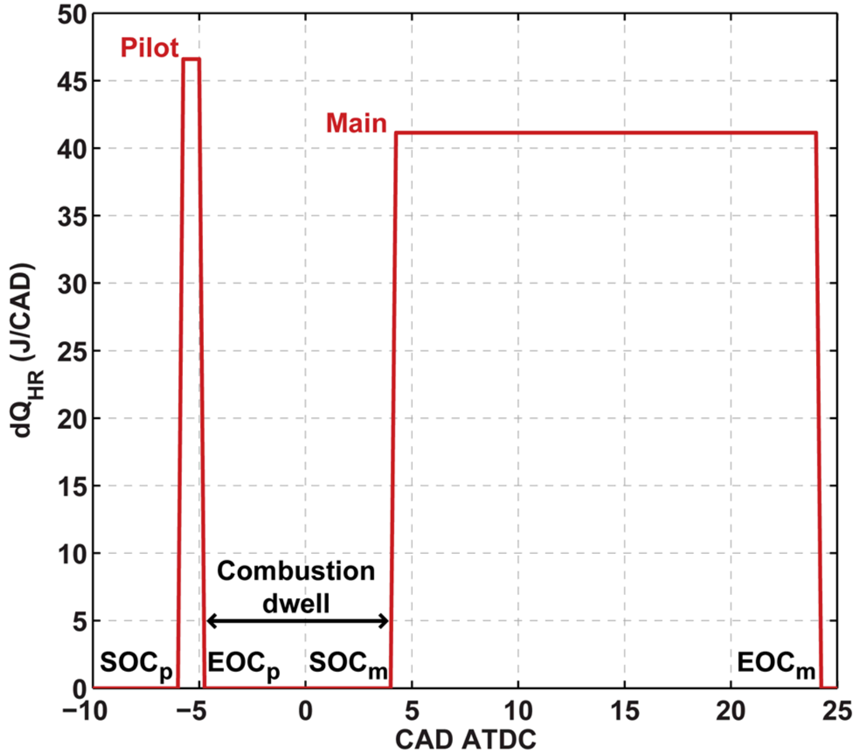
$$dQ = dQ_{heat\ release} - dQ_{woschni}$$

$$\gamma = 1.35 - 6 \cdot 10^{-5}T + 1 \cdot 10^{-8}T^2$$ (Brunt and Platts, SAE 1999-01-0187)

- Simulation input: heat release profile → $dQ_{heat\ release}$
- Simulation output: cylinder pressure trace, combustion noise

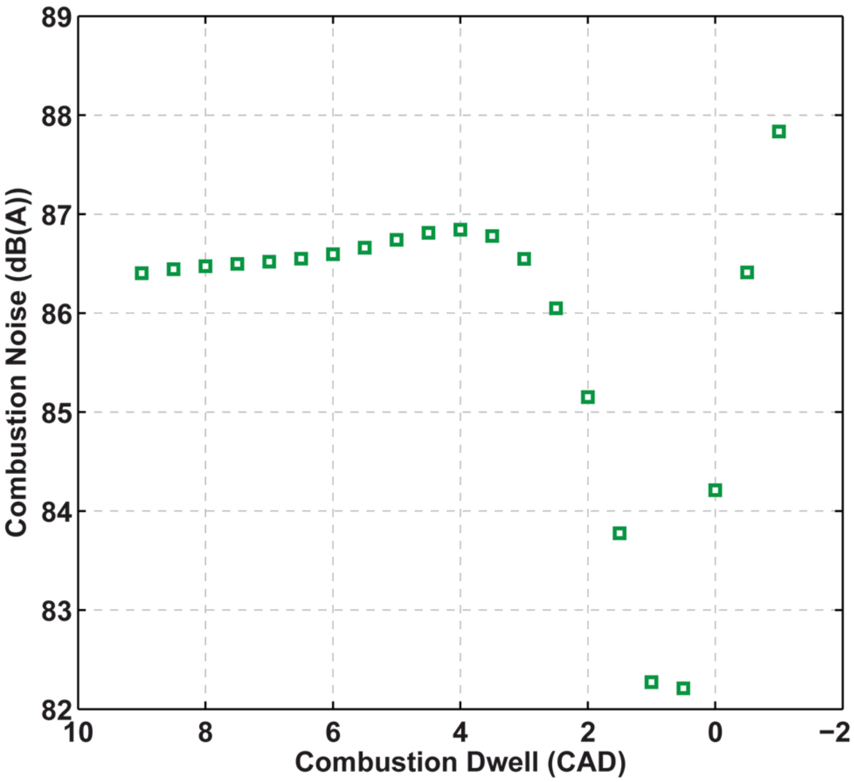
Simulation inputs: pre-defined heat release profiles

- Previous work: combustion noise behavior is well-predicted with realistic heat release profiles
  - SAE 2015-01-0796
- Shown here: simplified top hat heat release profiles are used to simplify analyses
  - Total heat release quantities approximate the measured data
  - Combustion dwell: duration between EOC_p and SOC_m
  - Does the close-coupled pilot noise reduction exist with these simple heat release profiles?



The close-coupled pilot noise reduction occurs with top-hat heat release profiles

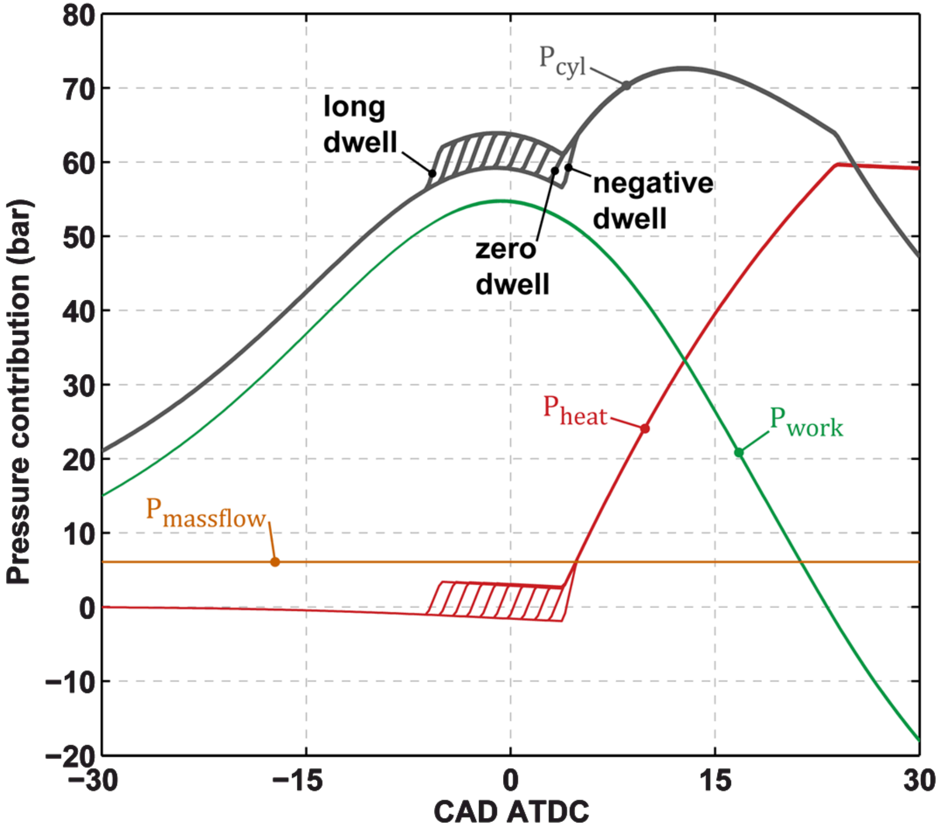
- Noise reduction mechanism remains intact
- Details of the noise-dwell curve depend on heat release profile shapes
  - Depth, width of valley, etc.
- What can we learn by digging into the terms of the governing equations?



Decomposition of the model's underlying equation for cylinder pressure

$$dP = \frac{(\gamma - 1)(dm_i h_i - dm_e h_e)}{V} + \frac{-\gamma P dV}{V} + \frac{(\gamma - 1)dQ}{V}$$

- $P_{massflow} = \int dP_{massflow}$
  - Not affected by dwell; not responsible for noise reduction
- $P_{work} = \int dP_{work}$
  - Contributes to overall shape of the pressure trace, but not to the noise reduction mechanism
- $P_{heat} = \int dP_{heat}$
  - Changes significantly with dwell; includes wall heat loss and heat release
  - Can be decomposed further



Decomposition of the model's underlying equation for cylinder pressure (cont.)

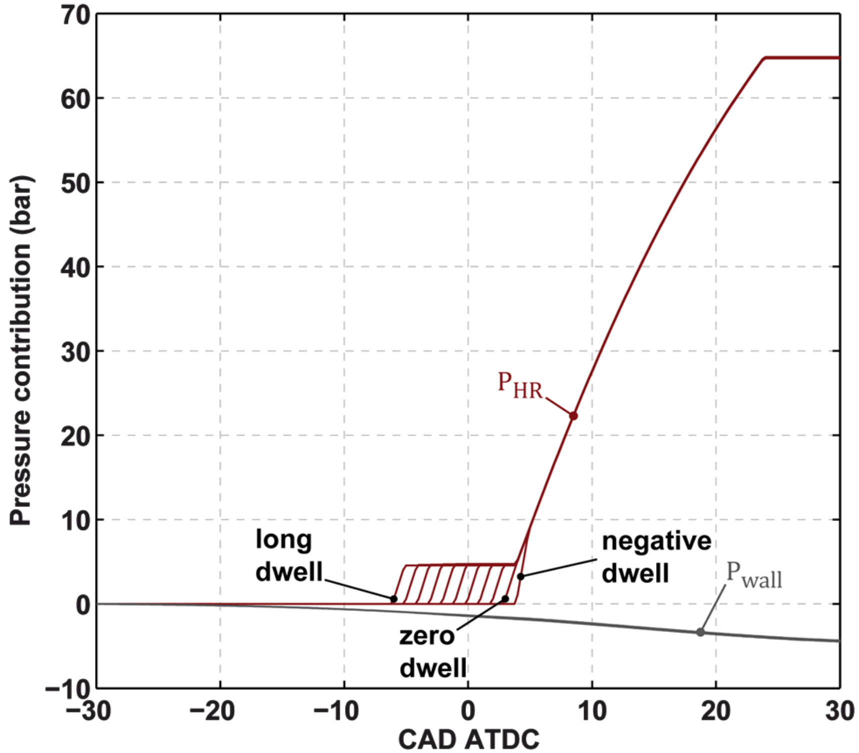
$$dP_{heat} = \frac{(\gamma - 1)dQ_{wall}}{V} + \frac{(\gamma - 1)dQ_{HR}}{V}$$

$$P_{wall} = \int \frac{(\gamma - 1)}{V} dQ_{wall}$$

- Not affected by dwell; not responsible for noise reduction

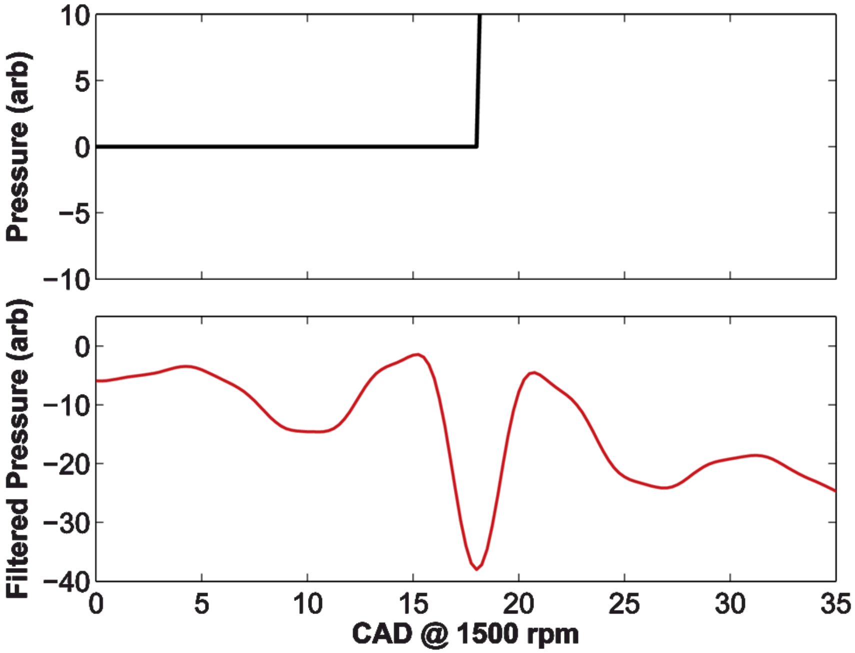
$$P_{HR} = \int \frac{(\gamma - 1)}{V} dQ_{HR}$$

- This term is fundamentally related to the combustion noise reduction mechanism
- It resembles two superimposed ramped step-functions



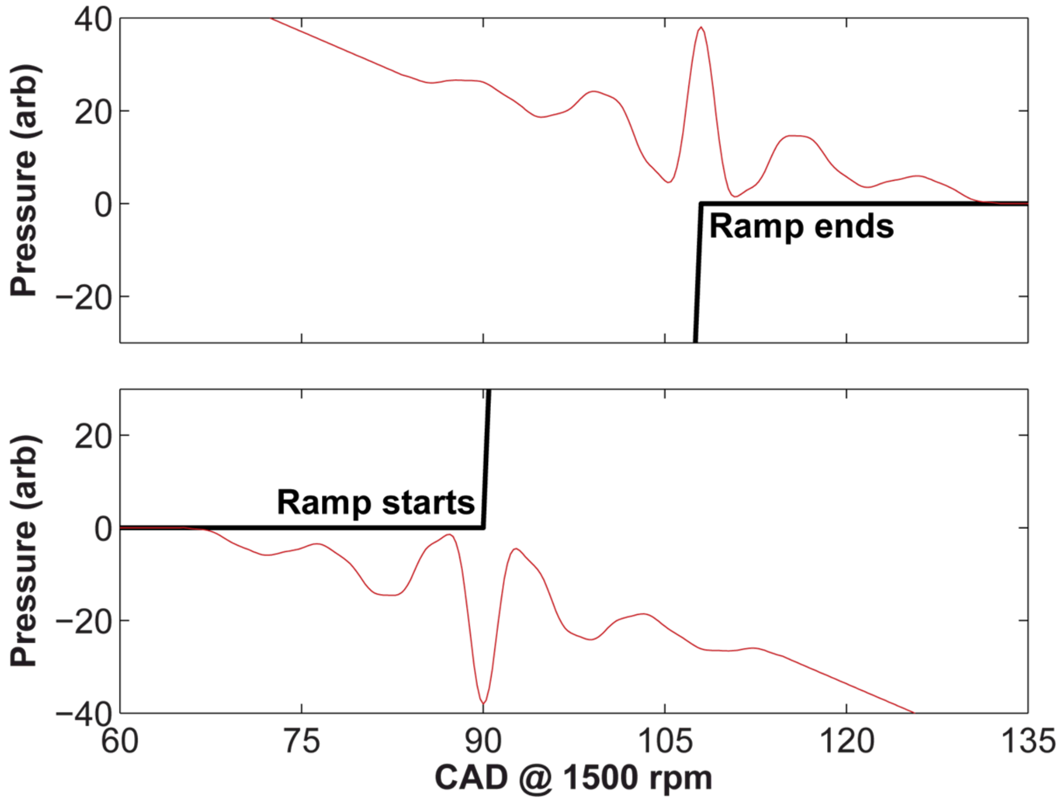
Band pass filtering of a ramp start

- Top: starting portion of a very long pressure ramp of variable slope
- Bottom: band-limited portion of the same pressure ramp
  - Finite impulse response (FIR) band pass filter: 1-3 kHz
- An abrupt increase in slope produces strong band-limited oscillations near the “corner”
  - A larger slope means higher band-limited oscillation amplitudes
- What about the end of a pressure ramp?



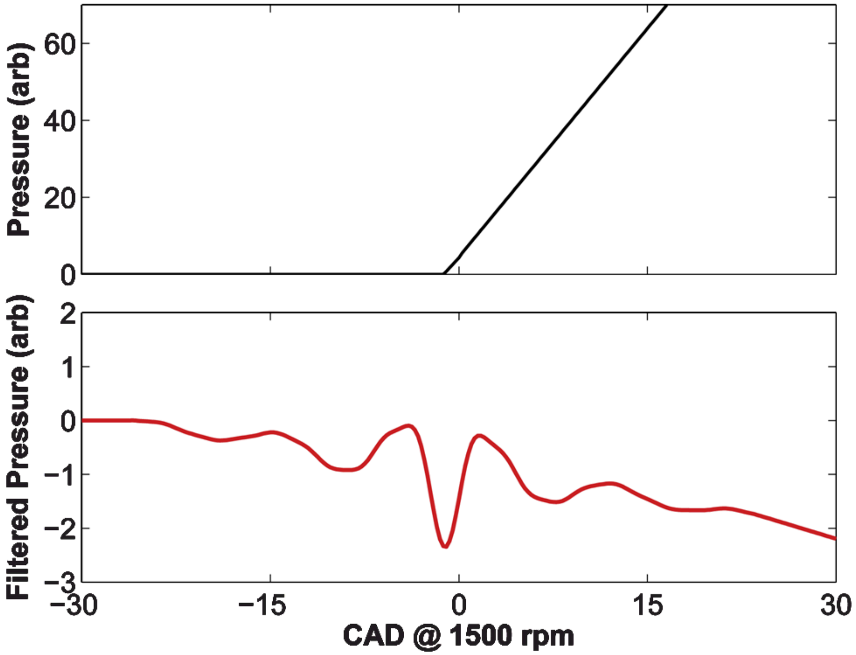
Band pass filtering of the start and end of a positive ramp

- Pressure oscillations at the end of a positive ramp (top) are an inverted image of the oscillations at the start of the ramp (bottom)
- Every ramped step is a combination of these two features
  - Pilot: ramp start followed closely by ramp end
  - Main: ramp start, long ramp, followed by ramp end



Combustion noise reduction through destructive interference

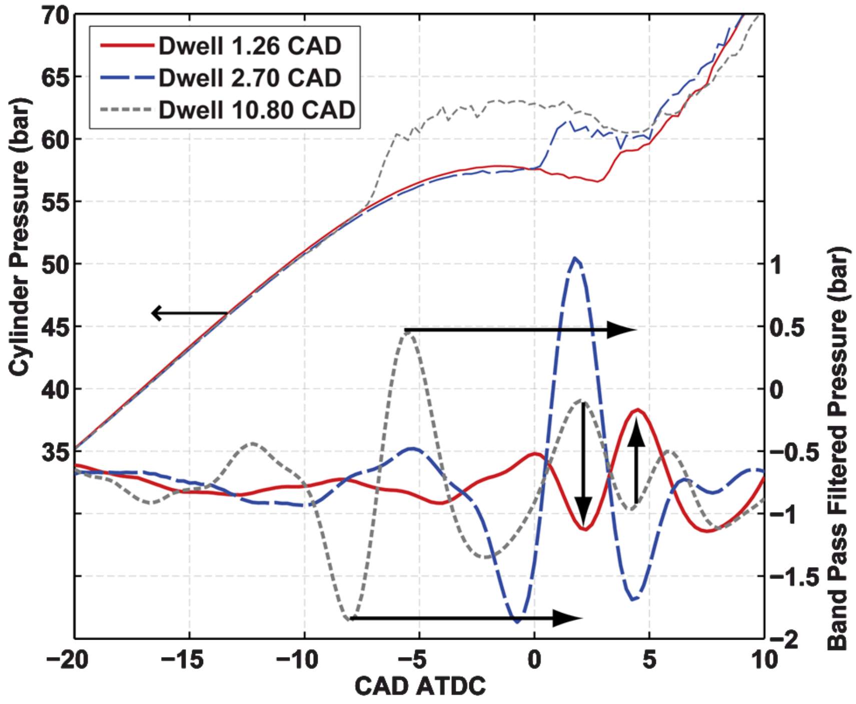
- Band-limited pilot ramp: trough followed by peak
- Band-limited main ramp: two peaks surrounding a trough
- Superposition of these two band-limited pressure traces with variable phasing
- Frequency content in 1-3 kHz band is attenuated through destructive interference
- **This is the heart of the close-coupled pilot combustion noise reduction mechanism!**



For more detail: Busch, S., Zha, K., Warey, A., Pesce, F. C. and Peterson, R., "On the Reduction of Combustion Noise by a Close-Coupled Pilot Injection in a Small-Bore Direct Injection Diesel Engine," Journal of Engineering for Gas Turbines and Power 2016, DOI: 10.1115/1.4032864

Evidence of destructive interference with close-coupled pilots: real data

- Band-limited pilot ramp: trough followed by peak
- Band-limited main ramp: two peaks surrounding a trough
- Dwell decreases; pilot and main oscillations begin to interact
- Minimum combustion noise: destructive interference of pilot and main oscillations is maximized
- **Destructive interference of higher frequency components (1-3 kHz in this case) can reduce combustion noise in an engine!**



Ignition processes in piloted diesel jets – some open questions for engine operation

- Where does the pilot combustion take place, and what is the state of the cylinder contents at the start of the main injection?
- How does the pilot influence / enhance main mixture ignition?
  - Thermal influence – local or global
  - Source of radicals
  - What is the role of cool flame chemistry?
- How do operating parameters impact main mixture ignition?
  - Pilot timing and mass
  - Injection pressure
  - Injector design
- How is main mixture formation and ignition in an engine different than in an injection chamber?
  - Slipstream effect
  - Interaction with combustion chamber geometry
  - Bulk flow structures / turbulence
- Can main ignition processes be accurately simulated?

Experimental setup: high speed NL and OH* chemiluminescence imaging

- Natural luminosity (NL)
  - Primarily broadband radiation from soot; very strong function of temperature
  - NL indicates rich, hot combustion
- OH* chemiluminescence
  - $CH + O_2 \rightarrow OH^* + CO$
  - Spectral peak near 308 nm
  - Information about high-temperature ignition processes and flame structure
- Simultaneous high-speed imaging: 25 kHz
  - 0.36 CAD resolution at 1500 rpm

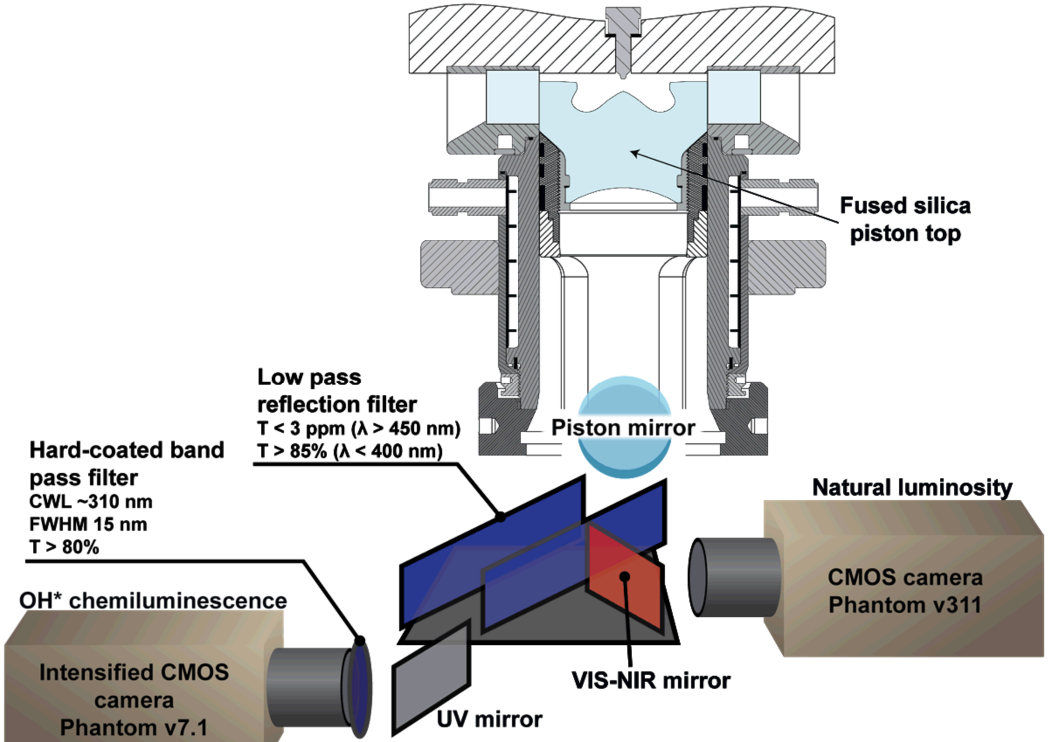


Image distortion correction

- Image distortion arises from the complex piston geometry
  - Depends on crank angle, varies with radial and axial object position
- A ray-tracing based algorithm is used to distortion correct both the NL and the OH* images
  - Algorithm requires *a priori* knowledge of signal origins
- Assumed signal origins:
  - Along jet axes in the bowl
  - Halfway between head and fire deck in squish region

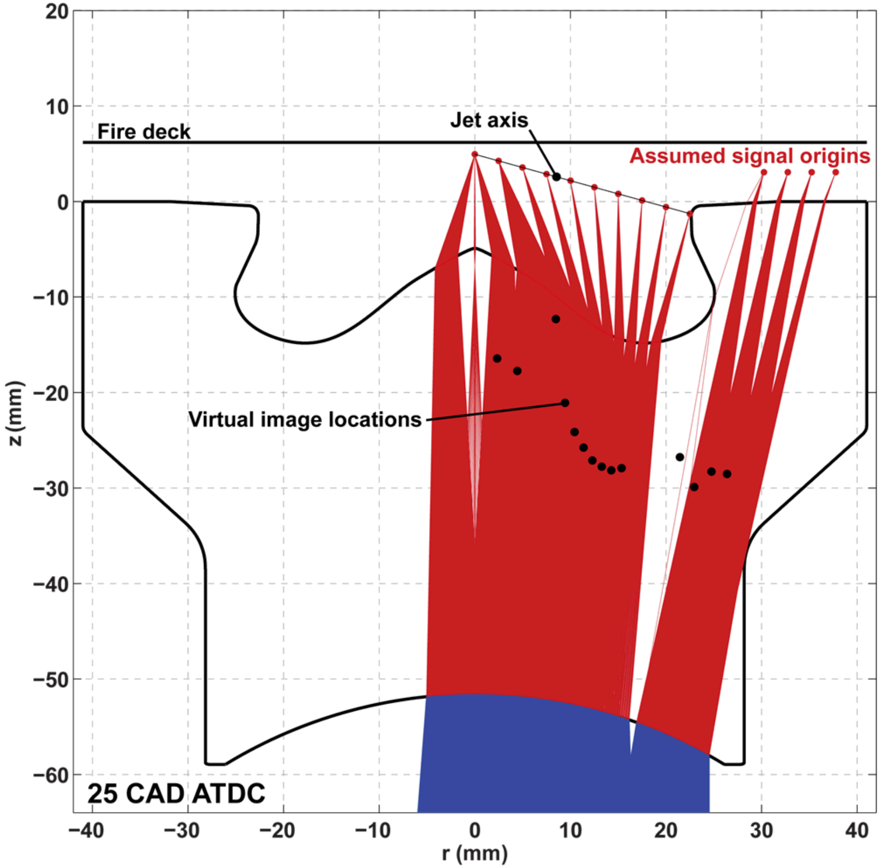
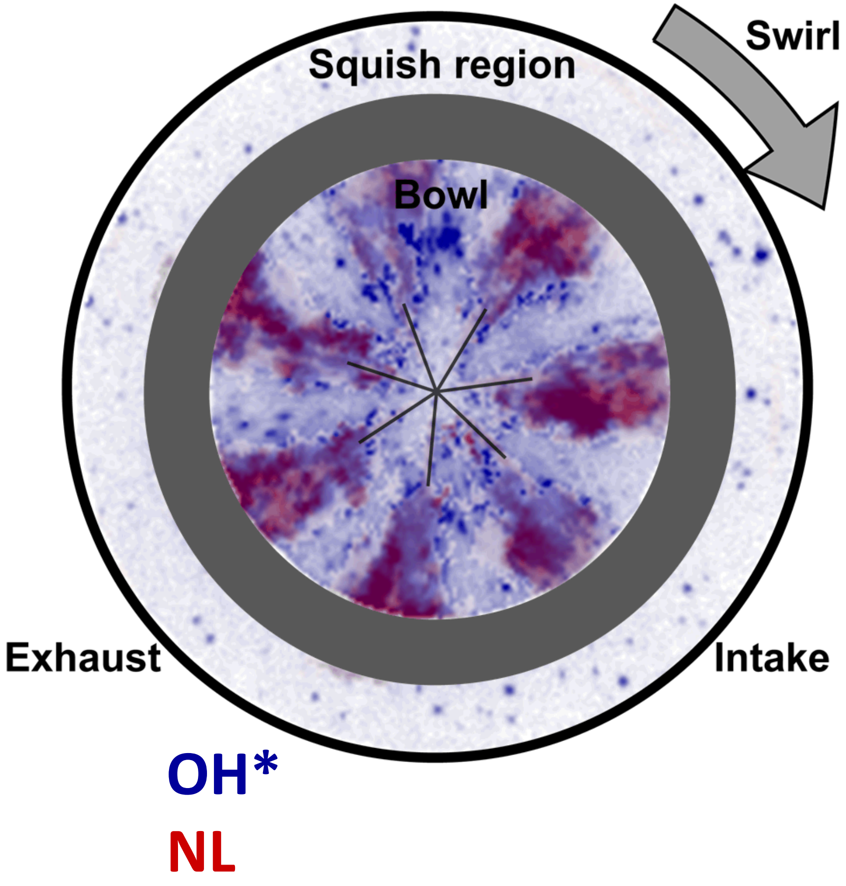


Image registration: OH* and NL Images

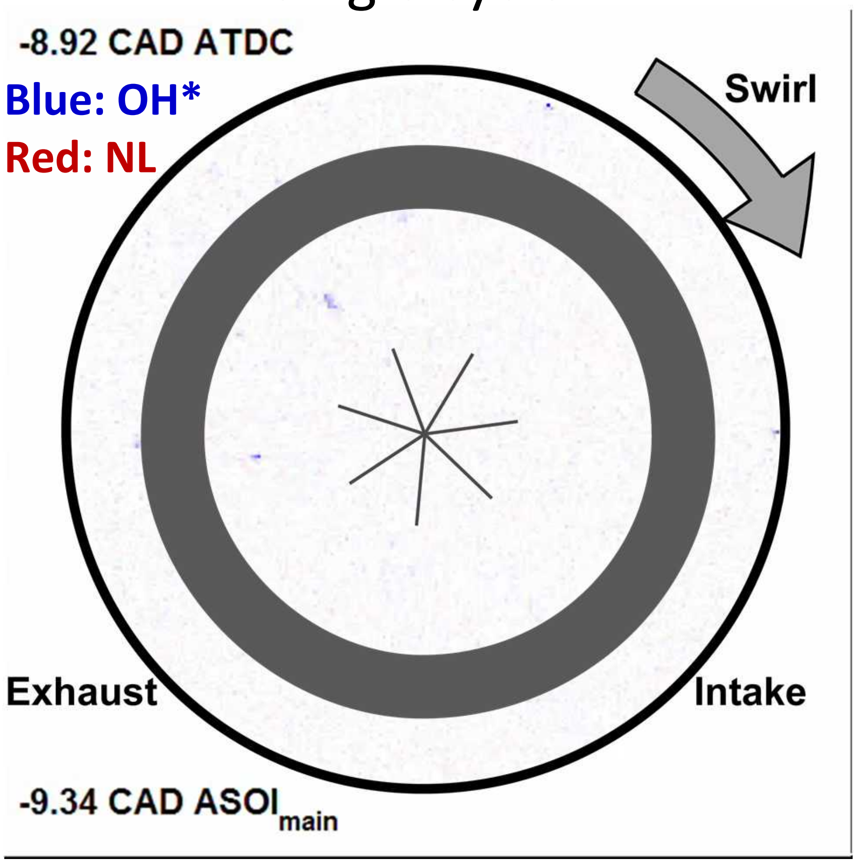
- OH* image: intensity scaled to emphasize location of detected OH* signal; shown with blue false-color
- NL image: scaled to increase visibility of lower intensity range; shown with red false-color
- OH* image serves as background; NL image is overlaid with 50% transparency
- Image intensities are not a quantitative measure of concentration or temperature
  - These images tell us when and where high-temperature and/or sooting combustion is taking place



Pilot combustion overview

- Pilot combustion is contained within the bowl
  - Combustion occurs close (< 10 mm) to the injector
- Initial reactions take place without NL emissions
  - Suggests that pilot fuel is well-mixed ($\phi < 2$)
- NL appears starting at maximum $AHRR_{pilot}$ (~6.8 CAD BTDC)
  - NL signal does not penetrate far into the cylinder
- Regions of OH* and NL persist after the end of pilot heat release and are visible at SOI_{main}

Single cycle

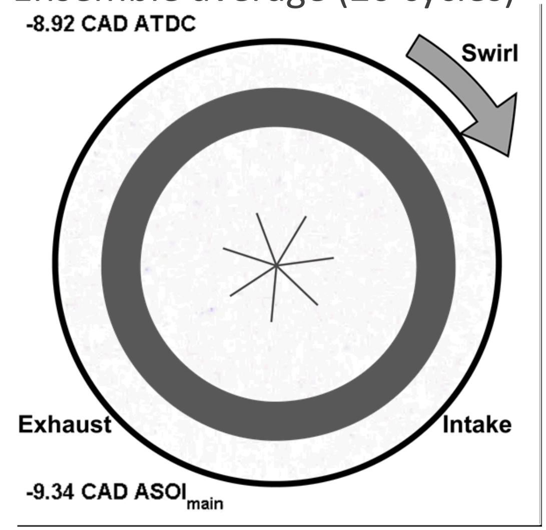


Rich, sooty portions of the pilot combustion are attributed to dribbled fuel

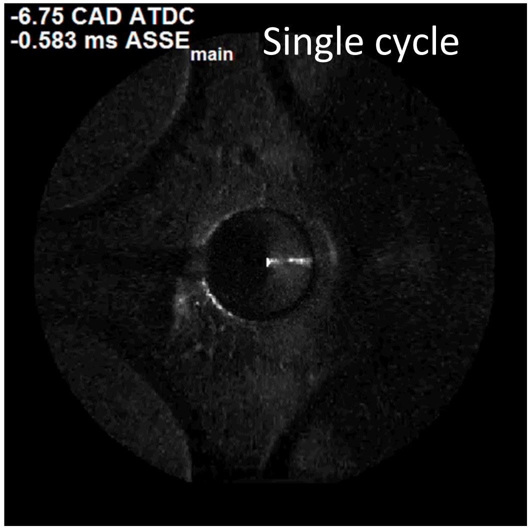
- Combined OH*-NL imaging (fired operation)
  - Similar NL behavior is observed in every cycle
  - Uneven distribution; NL first visible near peak of pilot HR

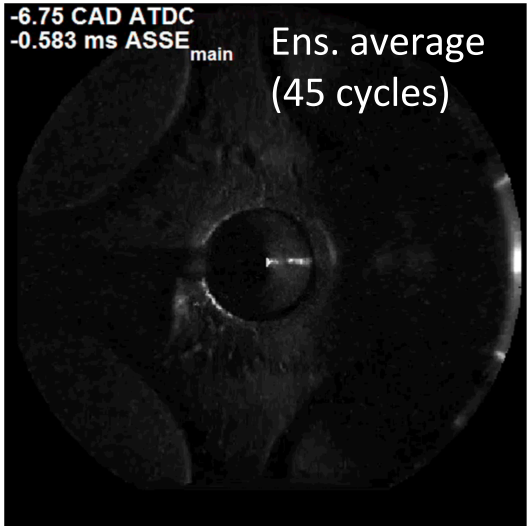
Blue: OH*
Red: NL

Ensemble average (20 cycles)



- Liquid fuel imaging (motored operation)
  - End of injection and dribble behavior are highly repeatable
  - There appears to be some correlation between jets with persistent liquid fuel and the appearance of NL during pilot combustion

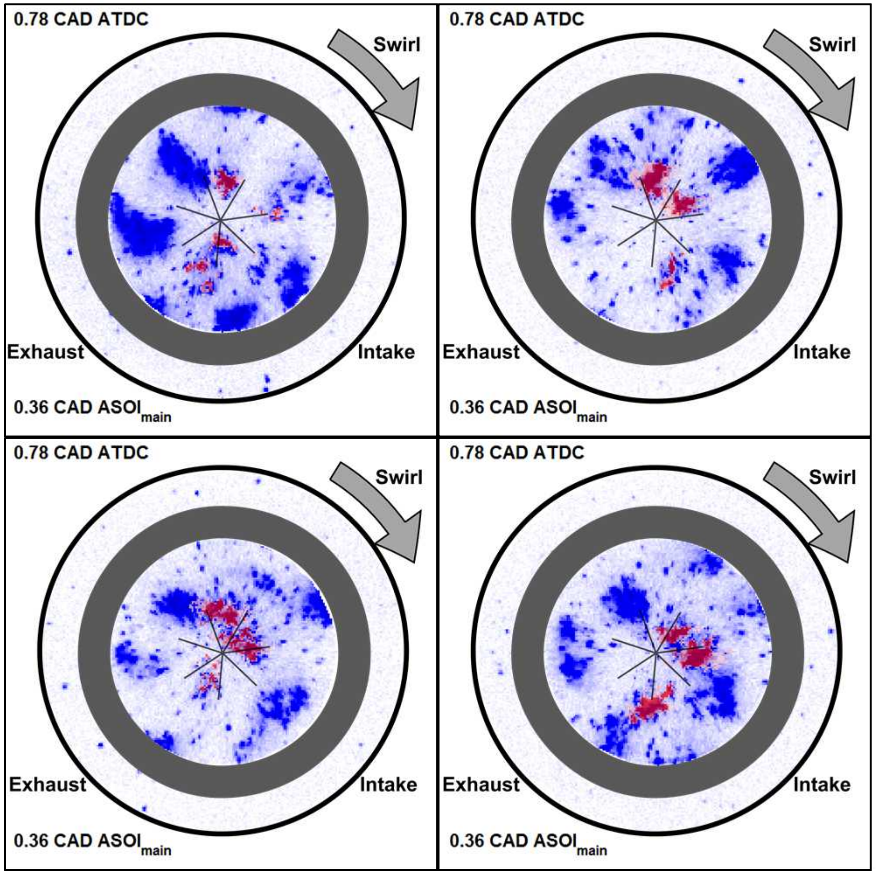




What is the state of the cylinder contents at SOI_{main}?

- Pilot heat release event has finished, but both OH* and NL signals are observed
- Some mixing has taken place:
  - Transport by swirling flow
  - Turbulent diffusion
- Active radicals and combustion products are unevenly distributed
- Temperature field is likely inhomogeneous
- How does the main mixture ignite in this environment?

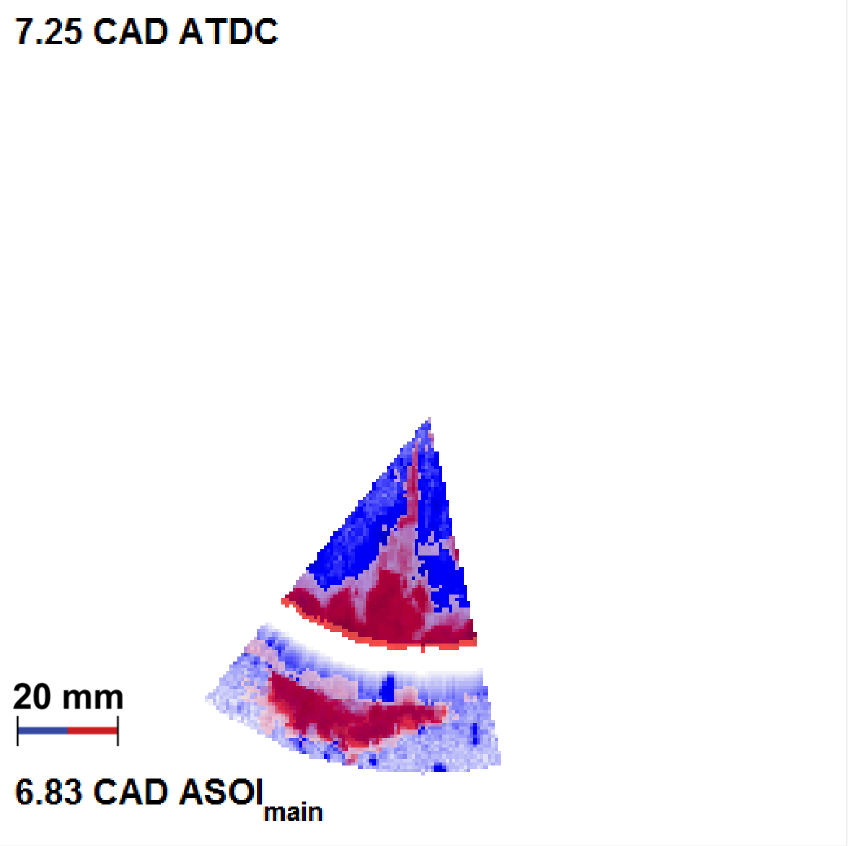
Images taken at SOI_{main}



Blue: OH*; Red: NL

Main ignition process for a single jet (1)

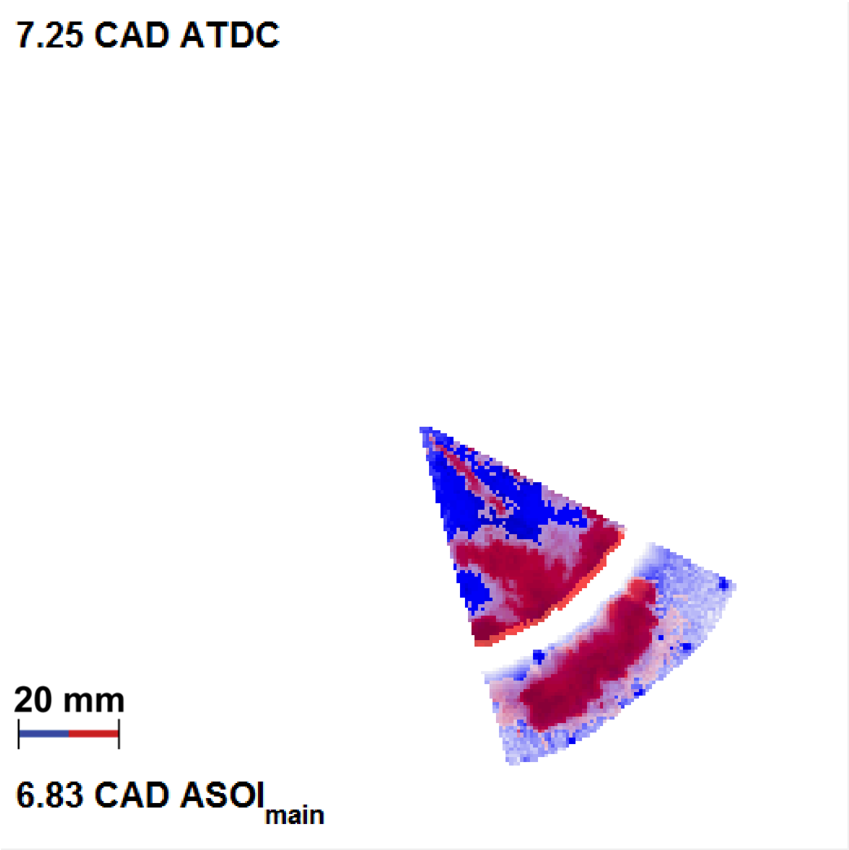
- SOImain: reactive pilot mixture deep in bowl, near injector tip
- OH* signaling the start of high temperature heat release first appears in multiple locations
- Ignition locations may be influenced by reactive pilot mixture (deep in bowl) or dribbled fuel (right side)
- Soot appears in head of jet as the jet takes on its familiar structure



Blue: OH*; Red: NL

Main ignition process for a single jet (2)

- SOI_{main}: NL and OH* near injector – rich combustion of dribbled fuel
- First OH* attributed to main mixture appears immediately downstream of dribbled fuel combustion, signal progresses downstream
- Soot is found throughout the jet in the early stage of ignition
  - Similar findings in [1]
  - Region of sooty combustion shifts downstream
- Jet structure develops; head of jet tangentially displaced by swirl

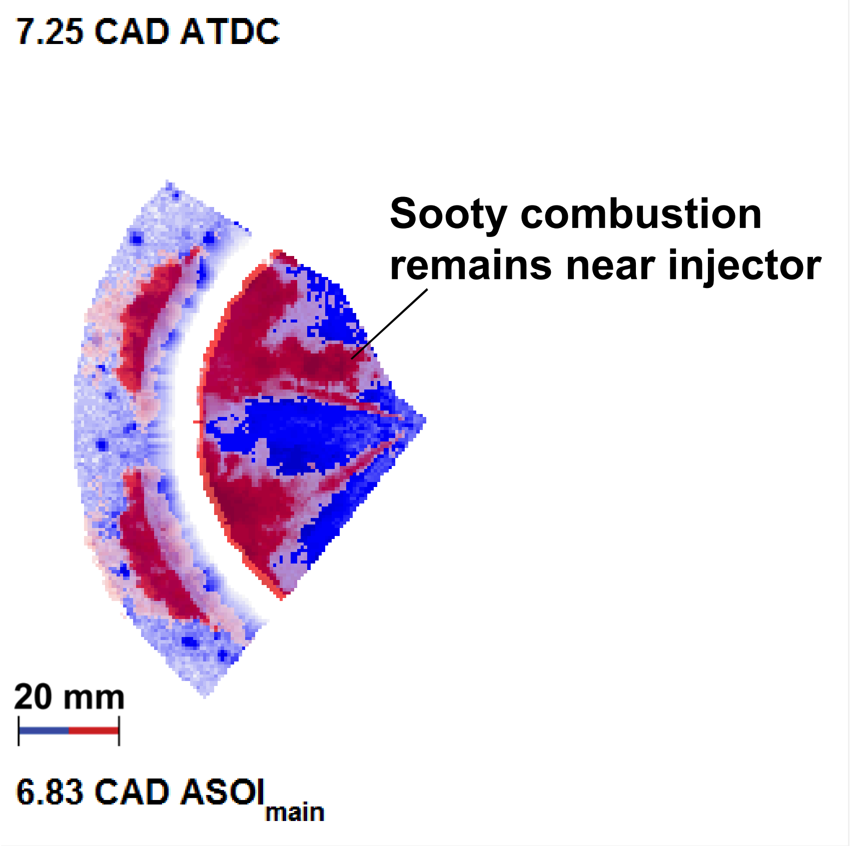


Blue: OH*; Red: NL

[1] Bruneaux, G. and Maligne, D., "Study of the Mixing and Combustion Processes of Consecutive Short Double Diesel Injections," *SAE Int. J. Engines* 2(1):1151-1169, 2009, doi:10.4271/2009-01-1352.

Main ignition process for a single jet (3)

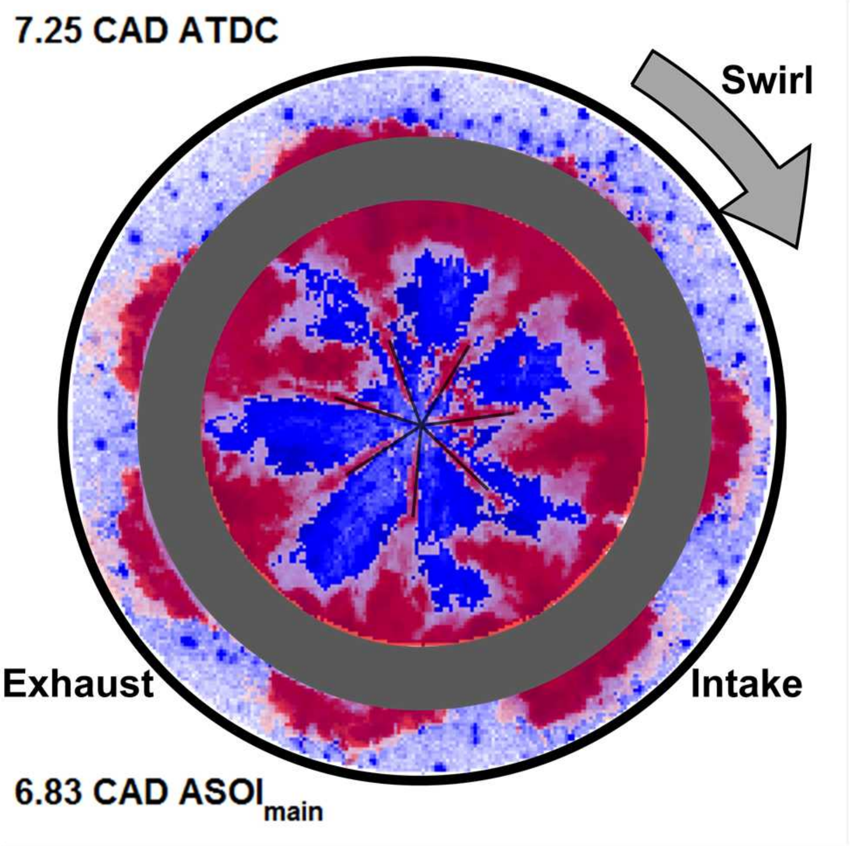
- SOI_{main}: reacting pilot mixture from jet of interest and from its neighboring jet
- Initial high temperature reactions take place several millimeters from the injector tip
  - NL is observed very near the injector tip shortly thereafter
- Isolated region of sooty combustion appears in jet head
  - Evidence of local ignition by interaction with the neighboring jet
- High temperature reactions quickly appear in remainder of jet
- Rich, sooty combustion remains near the injector



Blue: OH*; Red: NL

Recap: main ignition process with a single pilot injection

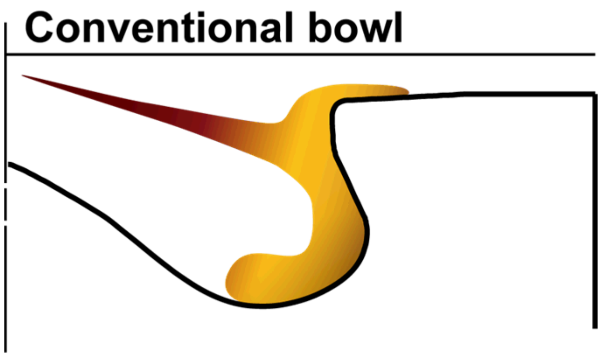
- The processes shown in the last three slides happen within one and the same cycle
- The main ignition process varies from jet-to-jet and cycle-to-cycle
- High temperature main ignition:
  - May begin at one or multiple locations within a jet
  - Influenced locally by pockets of reacting pilot/dribbled fuel
  - Can be influenced by reacting pilot mixture from the “up-swirl neighbor”
- Soot may initially form very near the injector
  - The location of initial soot formation may move downstream as the jet structure develops



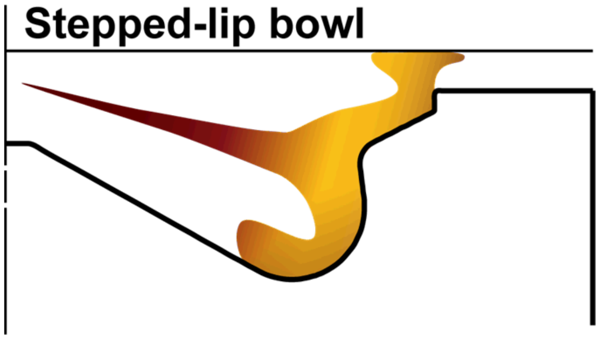
Blue: OH*; Red: NL

Piston bowl geometry: relevance for swirl-supported light- and medium-duty diesel engines

- **Stepped-lip bowls can be a cost-effective means to cleaner, more efficient diesel engines, but fundamental knowledge is lacking about how their advantages are realized and what their limitations and drawbacks are**
- These bowls are often used in medium-duty diesel engines and were recently introduced in light-duty diesels for several reasons:
  - Improved air utilization: reduced soot emissions[4, 5, 6]
  - Less soot-wall interaction: less wear/heat transfer[4, 5, 6]
  - Smaller surface area / reduced heat transfer[4, 5, 6, 7, 8]
  - Improved late-cycle mixing[6]; faster combustion rates[5, 6]

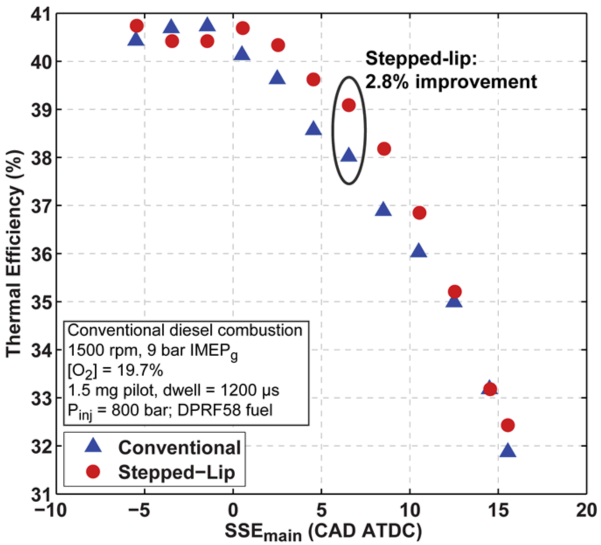


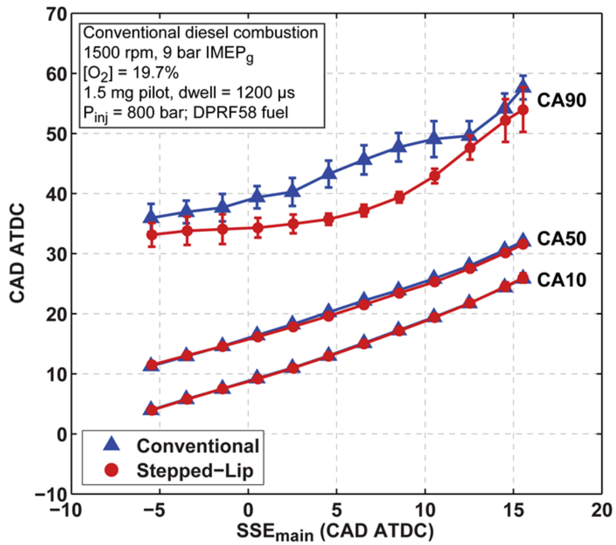
- Experiments (SNL) and 3D-CFD simulations (UW) are needed to provide insight into how piston geometry can impact mixture formation and late-cycle mixing in swirl-supported, direct injection engines

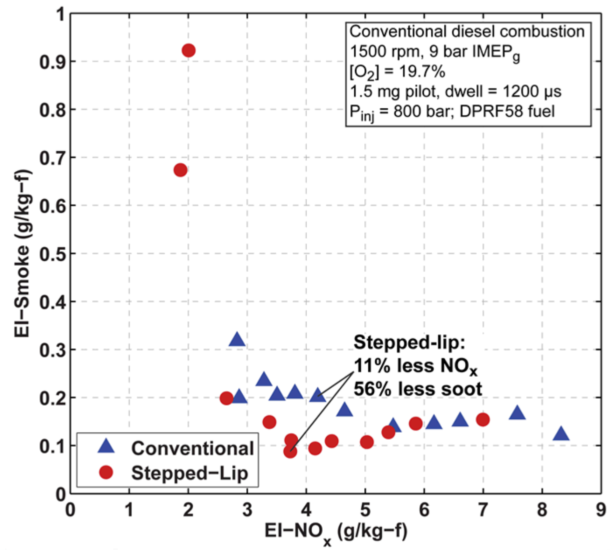


Piston bowl geometry influences late-cycle mixing, but also the soot-NOx tradeoff

- Conventional diesel combustion; conventional and stepped-lip pistons have been compared in terms of efficiency, emissions, and combustion phasing
  - With this stepped-lip piston, up to a 3% improvement in thermal efficiency can be achieved for main injection timings after TDC
  - The efficiency improvement is due in part to enhanced rates of late-cycle mixing-controlled combustion; this is in agreement with the literature[6]
  - Gains in efficiency can be realized with simultaneous reductions in soot and NO_x
  - Continuing work: analyzing heat transfer effects; investigating mixture formation differences and late-cycle mixing behavior





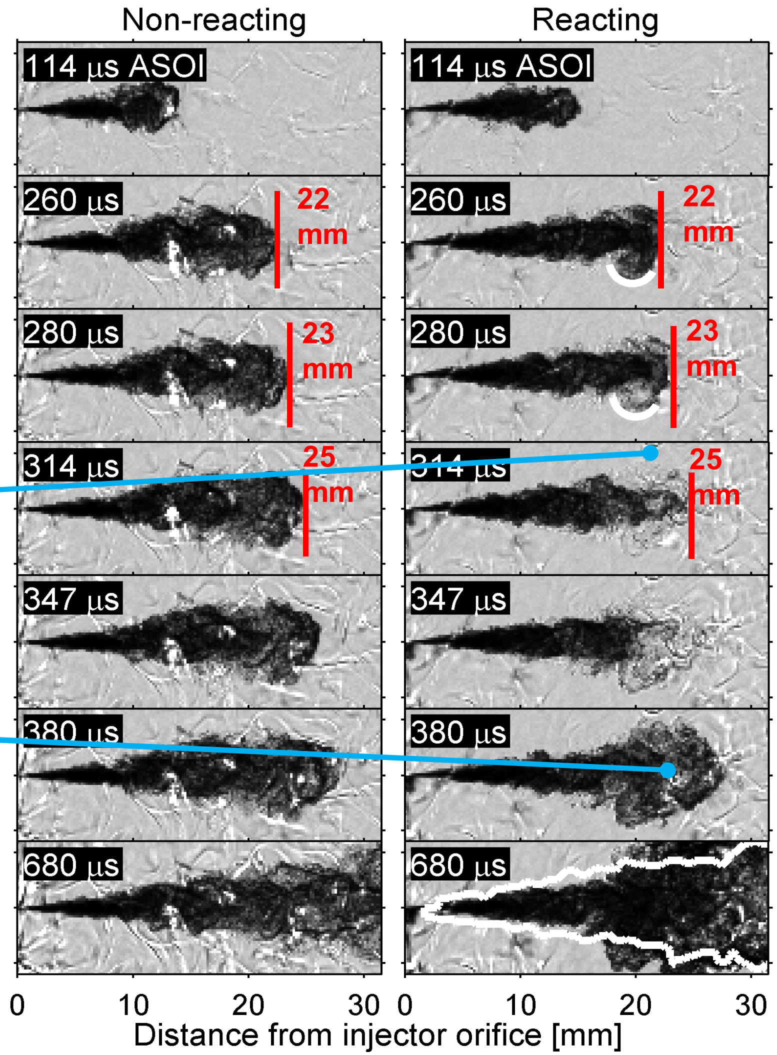


Thank you for your attention!

Questions?

Introduction: ignition processes in diesel sprays (single injection)

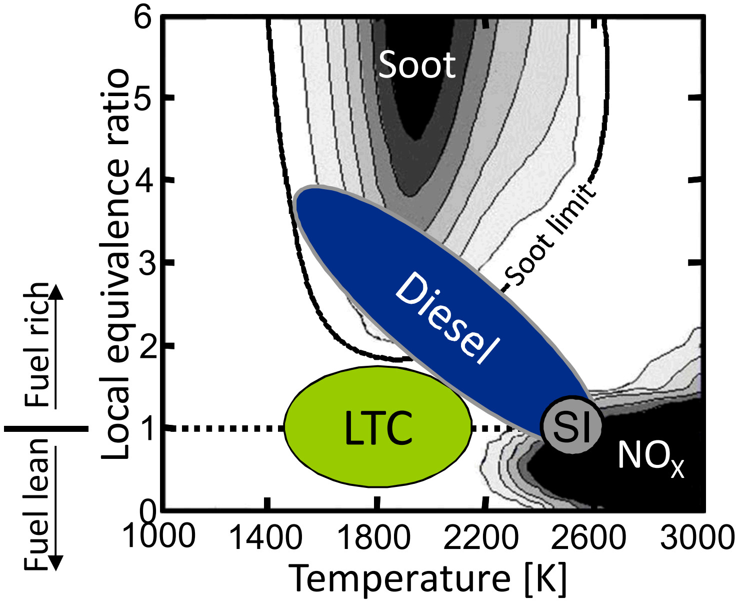
- Recent experimental efforts have provided a better understanding of single injection ignition processes: Skeen, Manin, Pickett (SNL)
  - Low temperature reactions start in hot, lean regions near the jet periphery, then propagate through jet head
  - Shortly afterward, high temperature ignition occurs volumetrically throughout large portions of the jet head



Images courtesy of S. Skeen, J. Manin, and L. Pickett (Aug. 2014 AEC meeting)

Research focuses on pathways to increased efficiency

- Stoichiometric, stratified charge & dilute or lean homogeneous spark ignition:
  Fuel-air mixing, ignition, knock suppression, stochastic processes (misfire) …
- Advanced diesel combustion: Fuel-air mixing, high-pressure and multi-pulse injection, lifted-flame combustion, asymmetry, bowl geometry …
- Low-Temperature Combustion (LTC):



  - Diesel LTC (PPCI, RCCI, MK, …)
  - Gasoline LTC (HCCI, LTGC, GCI)
  - *Challenges:*
    - Combustion phasing
    - Load range
    - Heat release rate
    - Transient control
    - HC and CO emissions
- Fuel effects on conventional and advanced combustion strategies (**Co-Optima**)

Research approach - closely coupled experiments and simulation

- Laser-based optical diagnostics.
- Optically accessible engines; realistic operating conditions
- Simulation
  - CFD in collaboration with partners
  - Developing next-generation simulation tools for engines (Large Eddy Simulation - LES).

In-depth analysis of the controlling physical/chemical processes

Time varying LES Grids
3-million cells, 137 blocks