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A Study of the Impact of Pilot-Main Dwell on Late-Cycle Flow in the Piston Bowl of a Light Duty Optical Diesel Engine

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Outline

- Introduction
  - Squish-swirl and injection-swirl interactions; relevance for Diesel engine development
  - Multiple injection strategies
- Experimental setup
  - Optical engine and operating point
- Combustion image velocimetry technique
  - High-speed natural luminosity imaging
  - Image distortion correction
  - Combustion image velocimetry
- Results
- Summary and conclusions
- Future work

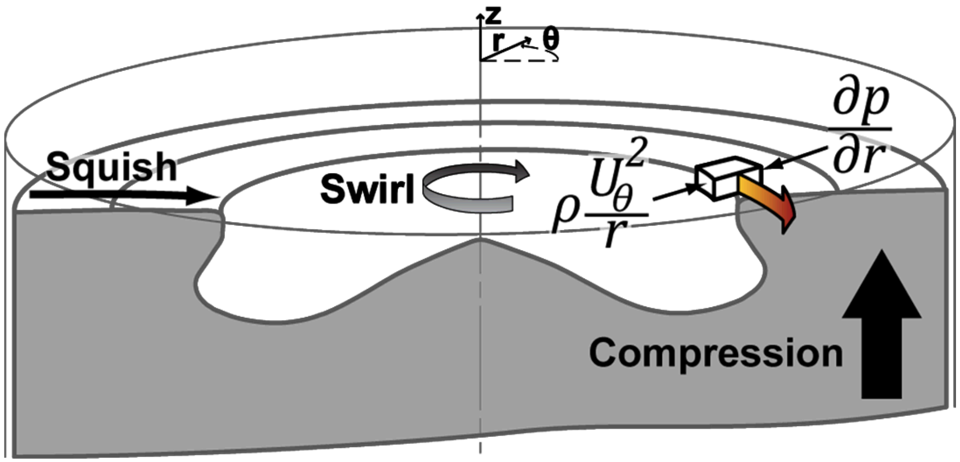
Introduction: squish-swirl interactions in swirl-supported Diesel engines

- Consider a fluid element rotating about the cylinder axis
- Equations of motion for steady flow

$$\rho \frac{Du_r}{Dt} = \rho \frac{{u_\theta}^2}{r} - \frac{\partial p}{\partial r}$$

$$\rho \frac{D(r\, u_\theta)}{Dt} = -\frac{\partial p}{d\theta}$$

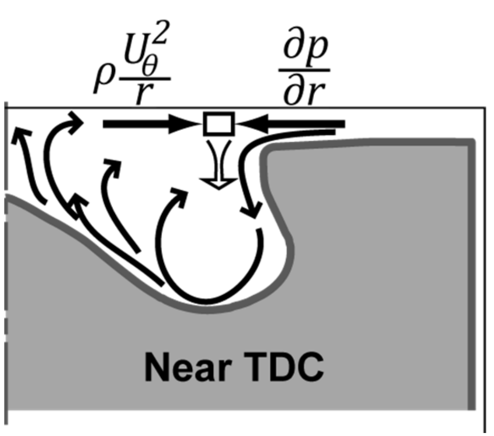
- Squish flow: fluid in the squish region is forced inward by piston motion
  - Conservation of angular momentum: tangential velocity increases
  - Centrifugal force increases
- The competition between centrifugal force and squish flow pushes fluid down into the piston bowl



Cutaway view of cylinder

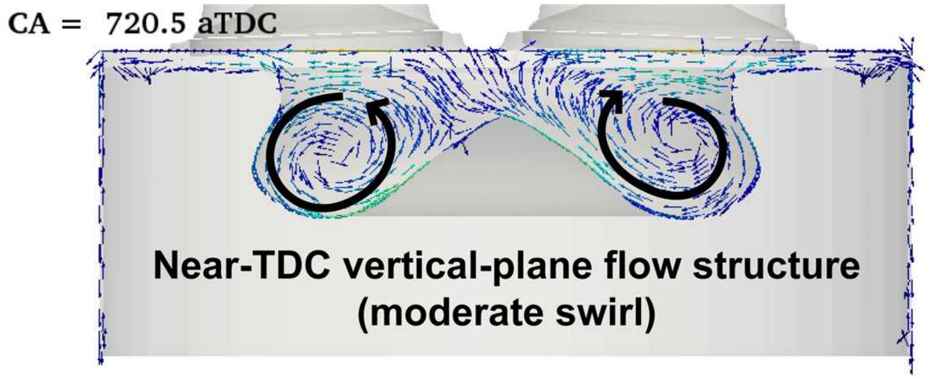
Moderate swirl (R_s ~ 2.5)

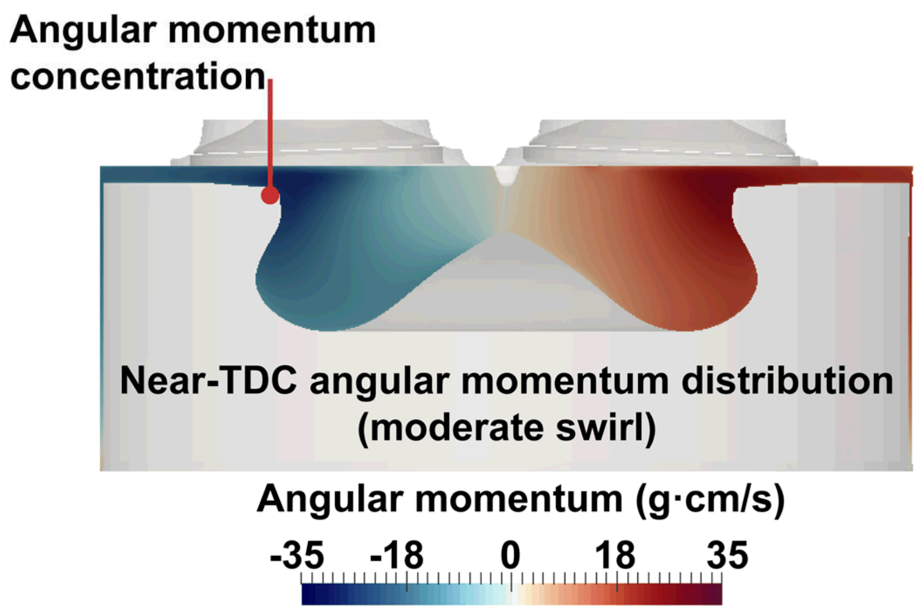
Formation of vertical-plane vortex structure



Introduction: injection-swirl interactions in swirl-supported Diesel engines

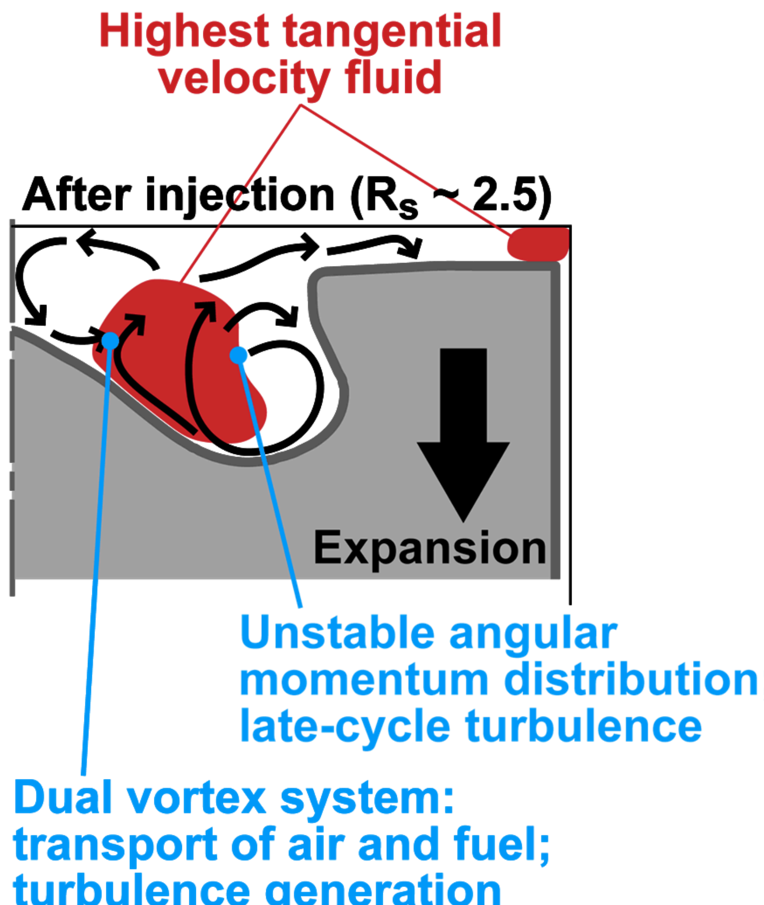
- Near-TDC vertical-plane flow
  - Toroidal vortex for moderate swirl ratios (3D-CFD results shown)
  - Angular momentum is concentrated near the bowl rim
- The fuel injection redistributes angular momentum[1,2,6]
  - Low-angular momentum fluid is entrained from the center of the chamber and transported into the bowl
  - High angular momentum fluid near the bowl rim is forced downward and inward in the bowl
- Redistributed angular momentum acts as stored energy that can be released as late-cycle turbulence





Introduction: importance of vertical-plane flow structures for emissions and efficiency

- After a single fuel injection, a dual-vortex system is often observed
  - Unburned fuel and air are transported to a common location where turbulent mixing promotes oxidation[1]
- Angular momentum has been redistributed by the injection and combustion-driven expansion[6,7]
  - Negative angular momentum gradients are unstable and an important source of late-cycle turbulence generation[5]
- Proper combustion chamber design supports the development of these flow structures, which can:
  - Simultaneously reduce NOx and soot[8]
  - Improve efficiency[8]



Introduction: effect of injection strategy on vertical-plane flow structures

- The impact of multiple injection strategies on angular momentum redistribution and vertical-plane flow structures is not well documented

- Andersson and Miles suggest that a pilot injection can influence both:

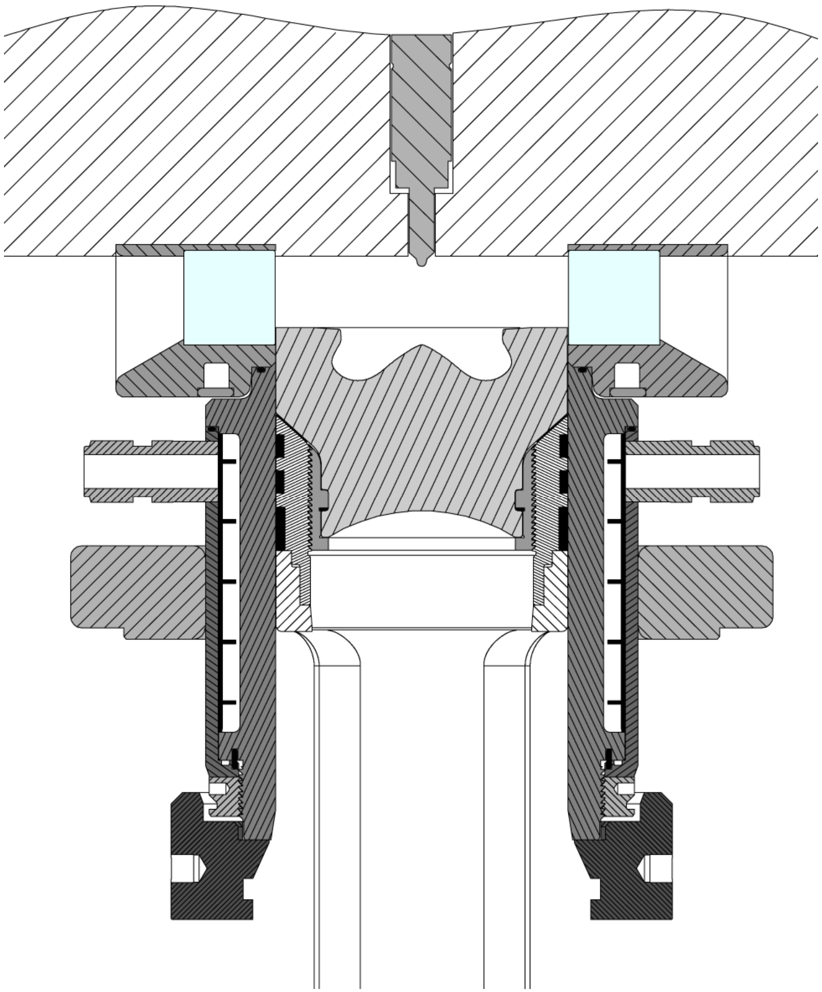
  "…a poorly designed pilot injection can displace the high angular momentum fluid from the region near the bowl lip, such that the fluid entrained and transported inward by the main injection does not possess the necessary high tangential velocity needed to create the desired vertical-plane flow structures"[2]

- The objective of this work is to develop an experimental technique to characterize the flow during combustion in the piston bowl of a light-duty, swirl-supported optical diesel engine with a simple pilot-main injection strategy

Experimental setup: single-cylinder light duty optical diesel engine

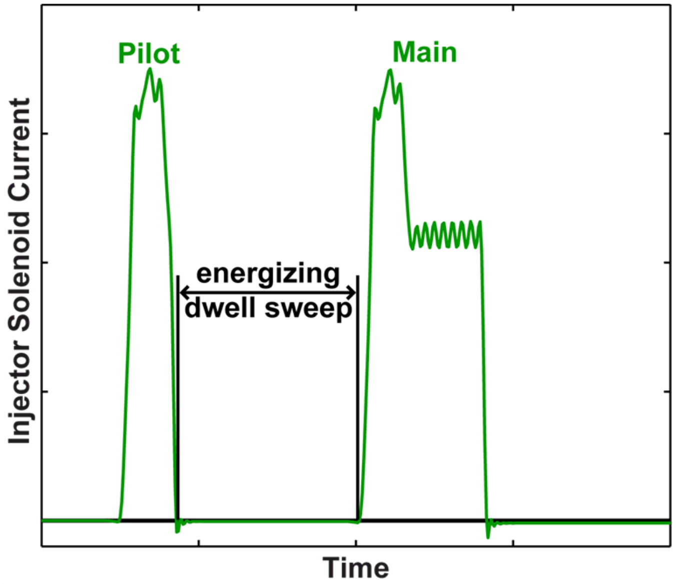
- GM 1.9L cylinder head
- Bowditch piston
- Re-entrant piston geometry; titanium and fused silica pistons

Bore x stroke	82 mm x 90.4 mm
Compression ratio	16.7:1
Valves	4
Piston geometry	Re-entrant bowl bowl:bore = 0.55
Injector	Solenoid; pressure-balanced pilot valve
Holes x Ø	7 x 139 µm
Conicity (ks)	1.5
Included angle	149°



Experimental setup: engine operating point

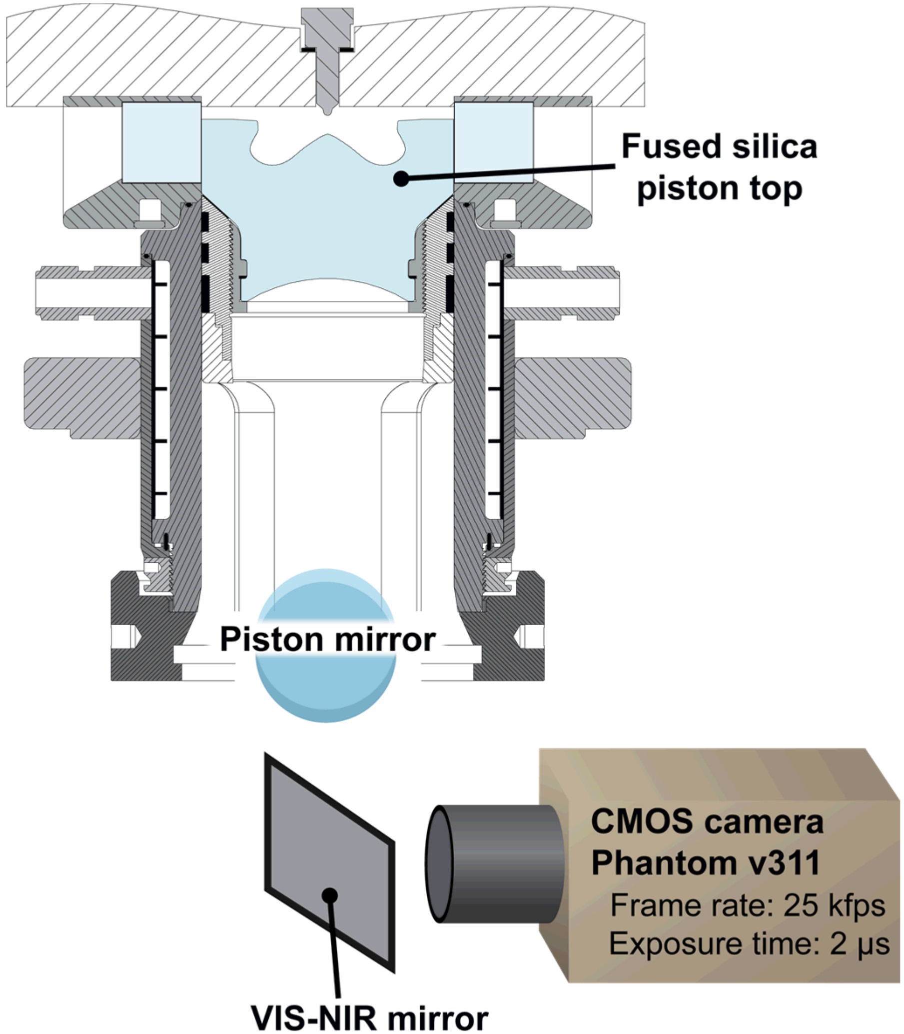
- Part-load operating point (conventional diesel combustion)
- Constant pilot mass, load, and combustion phasing (CA50)
- Skip-fired operation
- Pilot-main energizing dwell sweep



Engine speed	1500 rpm
Swirl ratio	2.2
IMEPg	9 bar
CA50	13 CAD ATDC
Rail pressure	800 bar
Pilot mass	1.5 mg/str
Pilot-main energizing dwell	1200, 500, 300, 140, 80 µs; 0 (main only)
EGR rate	10.3%
Fuel	42 vol% n-$C_{16}H_{34}$ (n-hexadecane) 58 vol% iso-$C_{16}H_{34}$ (heptamethylnonane)

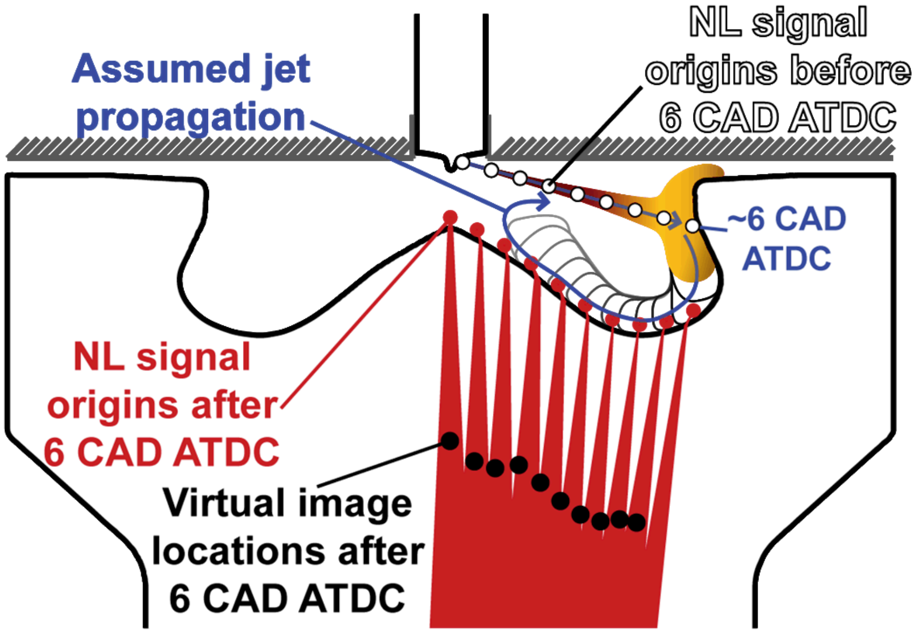
High-speed natural luminosity imaging technique

- Natural luminosity (NL): visible light emissions dominated by broadband soot radiation
- Images are taken through the bottom of the piston using a CMOS camera
- 2 μs exposure duration to minimize motion blur and utilize full dynamic range of camera
- 25 kfps frame rate for high temporal resolution
  - 0.36 CAD @1500 rpm



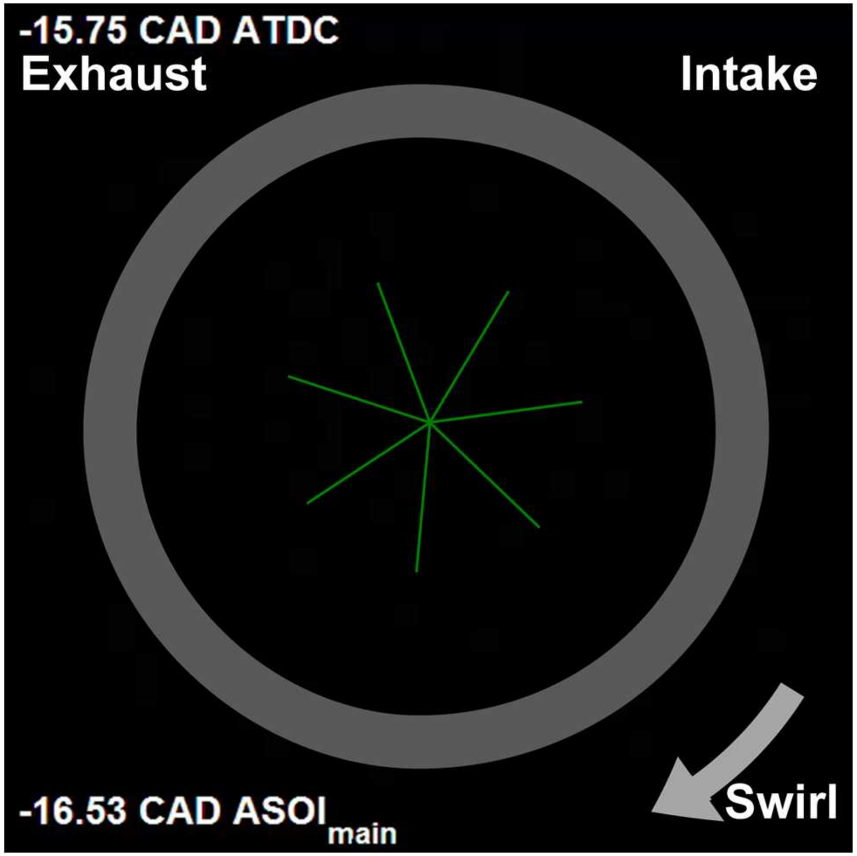
Interpretation of natural luminosity images

- Stages of spray flame propagation
  - Initial outward penetration
  - Redirection downward and inward by reentrant bowl
- Assumptions about NL signal origins:
  - Before jet reaches bowl rim, signal originates from jet axis
  - After jet reaches bowl rim, signal originates 1 mm above the bowl surface
- Raytracing simulations are used to automatically correct the distorted images
  - See ref. [14] for details



Distortion corrected images

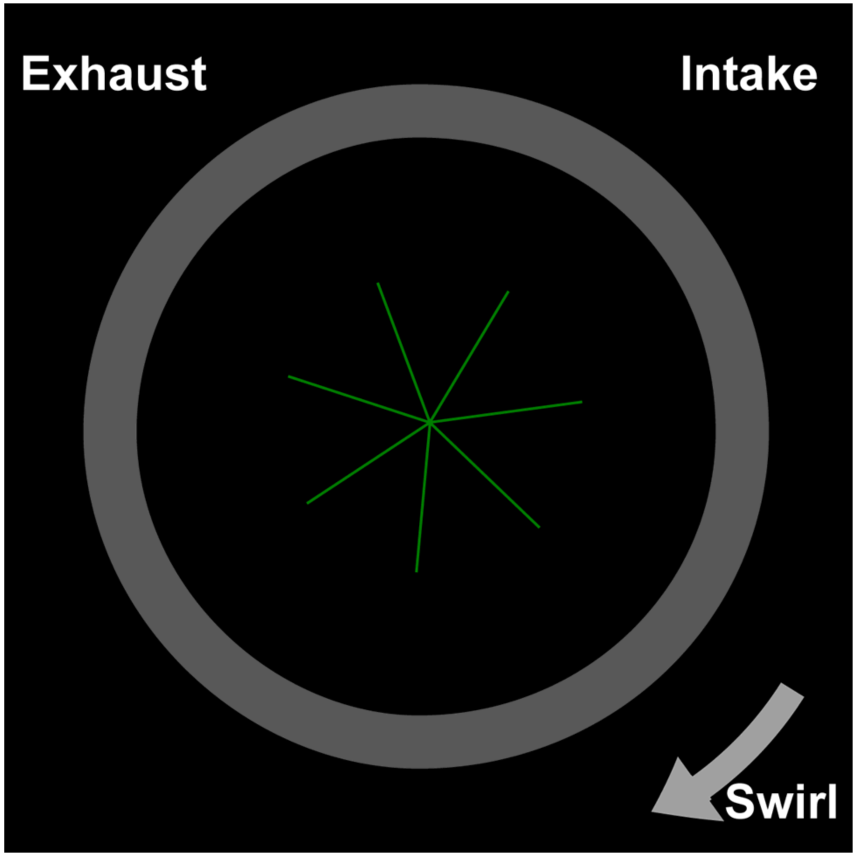
- Each frame is automatically distortion corrected
- Apparent jet propagation agrees with assumptions
- The fuel injection induces strong radial flow in the piston bowl
- The radial flow in the bowl is associated with vertical-plane flow structures (toroidal vortex)
- Can we quantify the radial flow behavior?



Sample: single cycle, 1200 μs dwell

Combustion image velocimetry (CIV)

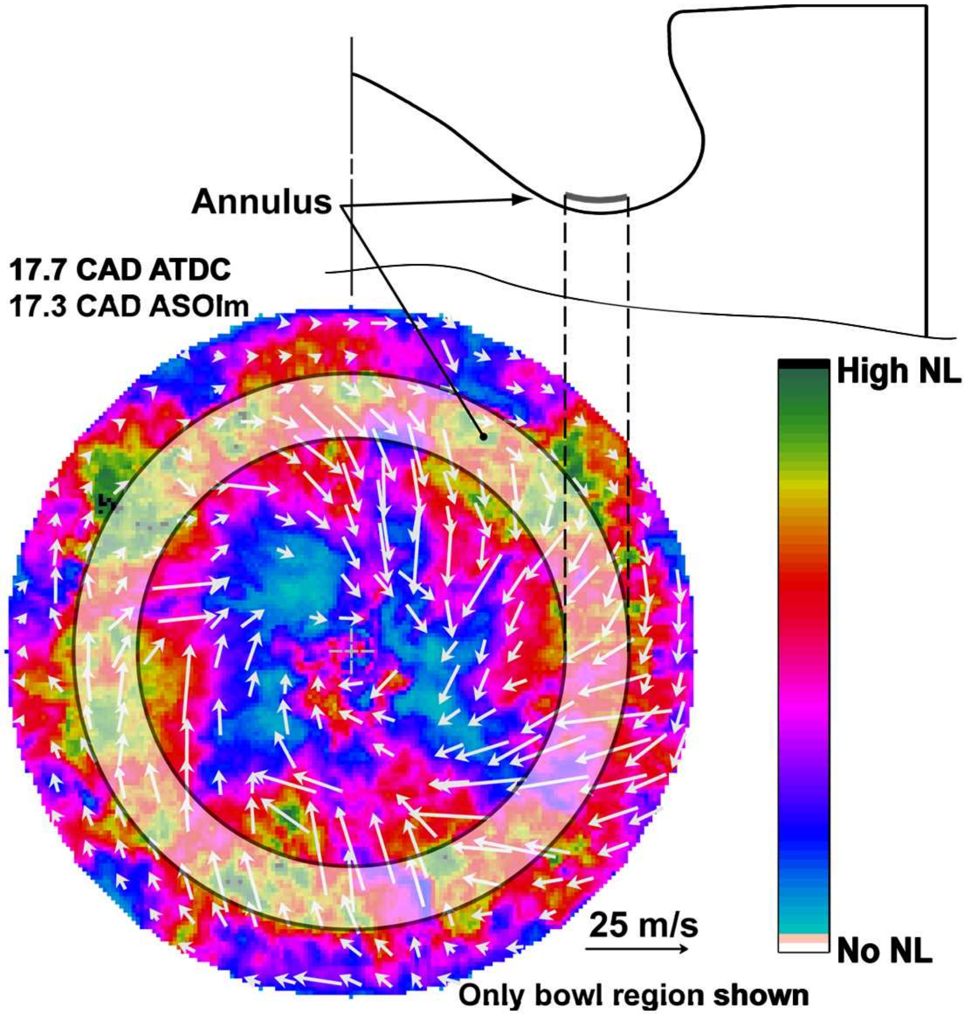
- CIV techniques have recently been developed and applied in optical diesel engines (see refs [12, 21-25])
- Correlation techniques utilize spatial inhomogeneity in NL images to track displacements and compute flow information
- High-speed NL imaging: temporal and spatial resolution
- Details of the CIV technique developed in this work are given in the paper



Sample: single cycle, 1200 μs dwell

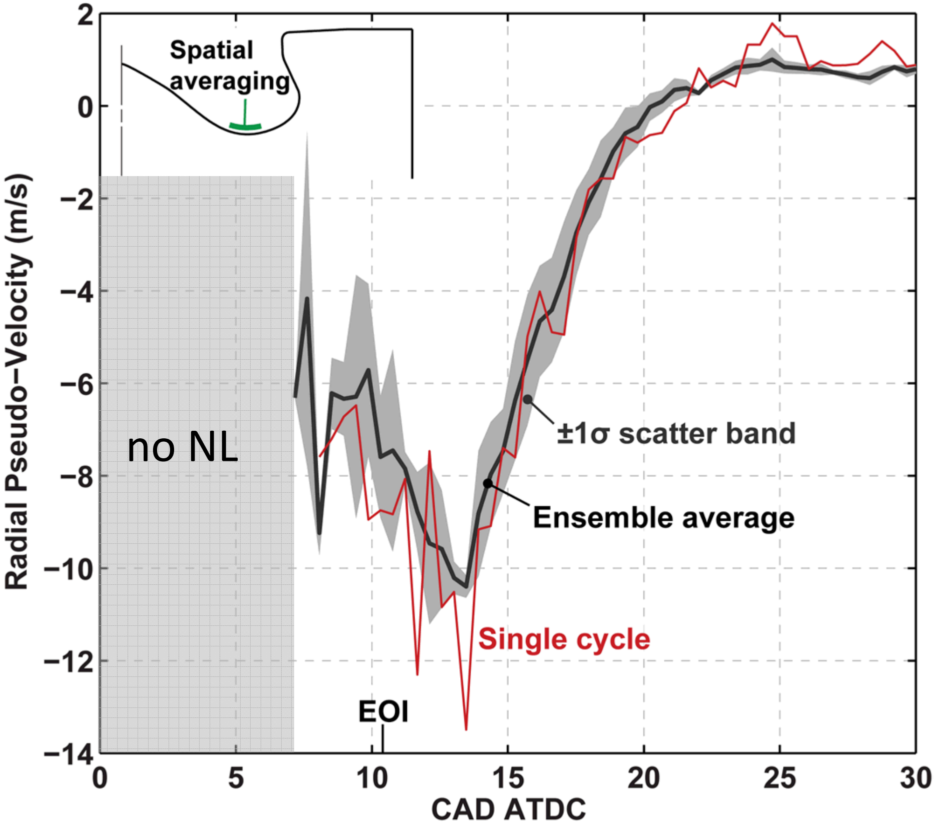
Analysis of CIV results

- Analysis is focused on an annular region in the deepest part of the bowl
- Each vector's radial component is computed
- The radial components are spatially averaged over the annular region deep in the bowl for each image
- The spatially averaged radial velocity is shown as a function of crank angle to represent radial flow behavior



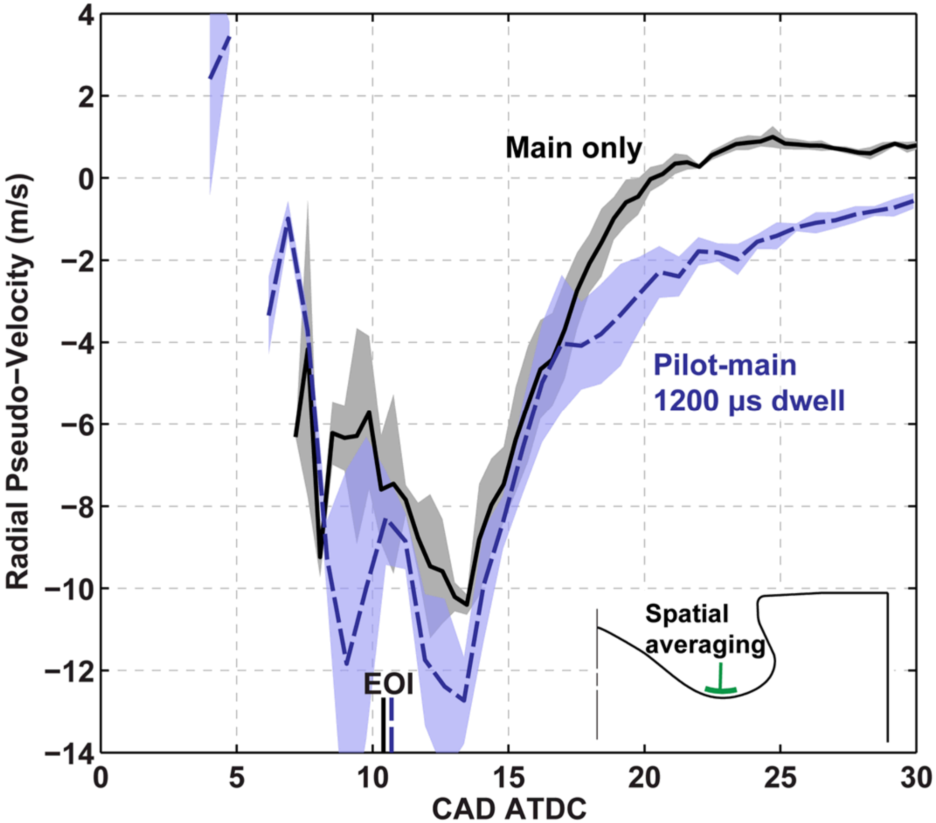
Results: radial flow behavior for a single injection

- Before 7 CAD ATDC, no NL signal is available – flow cannot be characterized
- Ensemble average curve computed for 20 fired cycles
- Initial radial velocity is negative: flow is directed inward
- Peak radial velocity is reached after EOI, near 13 CAD ATDC
- Radial velocity is positive after ~20 CAD ATDC
- Cyclic variability decreases during the later stages of combustion



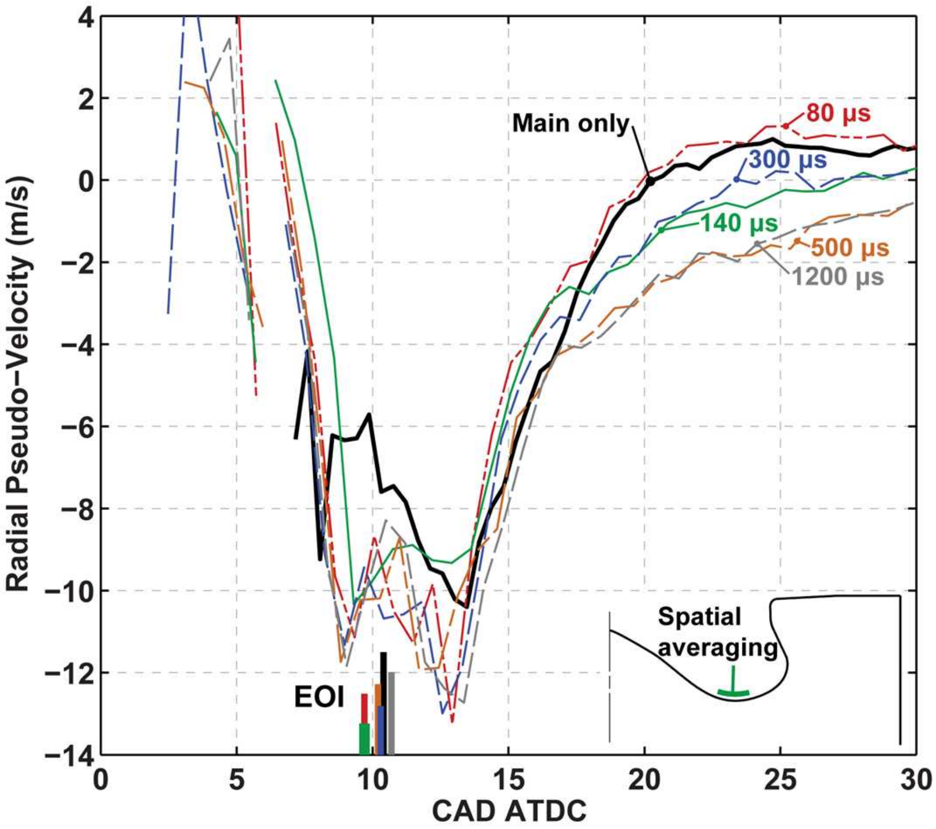
Results: radial flow behavior with a pilot injection (1200 µs dwell)

- NL is visible sooner with a pilot injection, so velocity information is available from an earlier crank angle
- Peak radial velocities are slightly higher with a pilot injection
- Radial flow behavior is qualitatively similar until ~17 CAD ATDC
  - Rate of radial flow decay decreases sharply with the pilot injection
  - The zero-crossing is delayed by more than 10 CAD



Results: radial flow behavior for the pilot-main dwell sweep

- Radial flow behavior is qualitatively similar for all dwells until ~15 CAD ATDC
- Start of radial velocity decay correlates with end of injection timing
- As dwell decreases, the impact on radial flow decay becomes smaller
- By changing the time between the pilot and main injections by ~1 ms, the late-cycle radial flow behavior in the bowl is significantly impacted



Summary and conclusions

- In swirl-supported Diesel engines, squish-swirl and injection-swirl interactions create beneficial vertical-plane flow structures that are important for transport of fuel and air, as well as turbulence generation
- The impact of multiple injection strategies on vertical-plane flow structures is not yet well documented
- A combustion image velocimetry technique was developed and applied in a light-duty optical diesel engine to investigate the effects of pilot-main dwell on flow behavior in the piston bowl
- Inward radial flow in the bowl reaches its maximum amplitude shortly after the end of injection, after which it decays
- Pilot-main dwell impacts the late-cycle radial flow behavior: longer dwells lead to slower late-cycle decay

Future work

- Pilot injections affect late-cycle flow behavior, but this line-of-sight imaging technique can only provide limited information about what may be happening in the combustion chamber

- 3D-CFD simulations are ongoing; if late-cycle phenomena can be captured with a simulation, then the simulation can provide significant insight about the impact of pilot injections on:
  - Angular momentum redistribution
  - Behavior of vertical-plane flow structures
  - Late-cycle turbulence generation
  - Soot oxidation processes

Thank you for your attention!

Questions?

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