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Numerical and Experimental Studies of a Novel Dimpled Stepped-Lip Piston Design on Turbulent Flow Development in a Medium-Duty Diesel Engine

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Introduction and Motivation

- Piston bowl shape strongly affects the engine efficiency and emissions
- Reducing emissions without penalizing efficiency is difficult,
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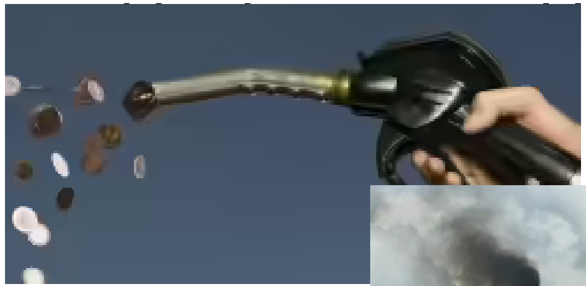
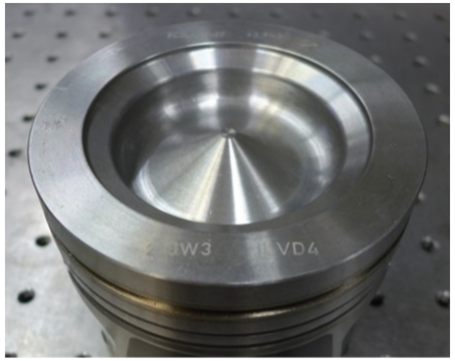
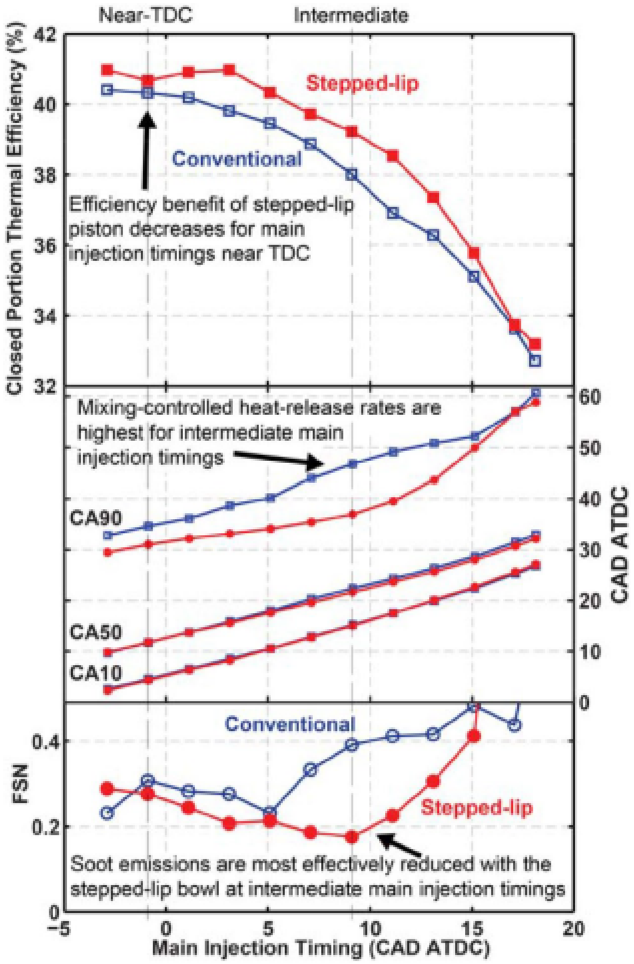




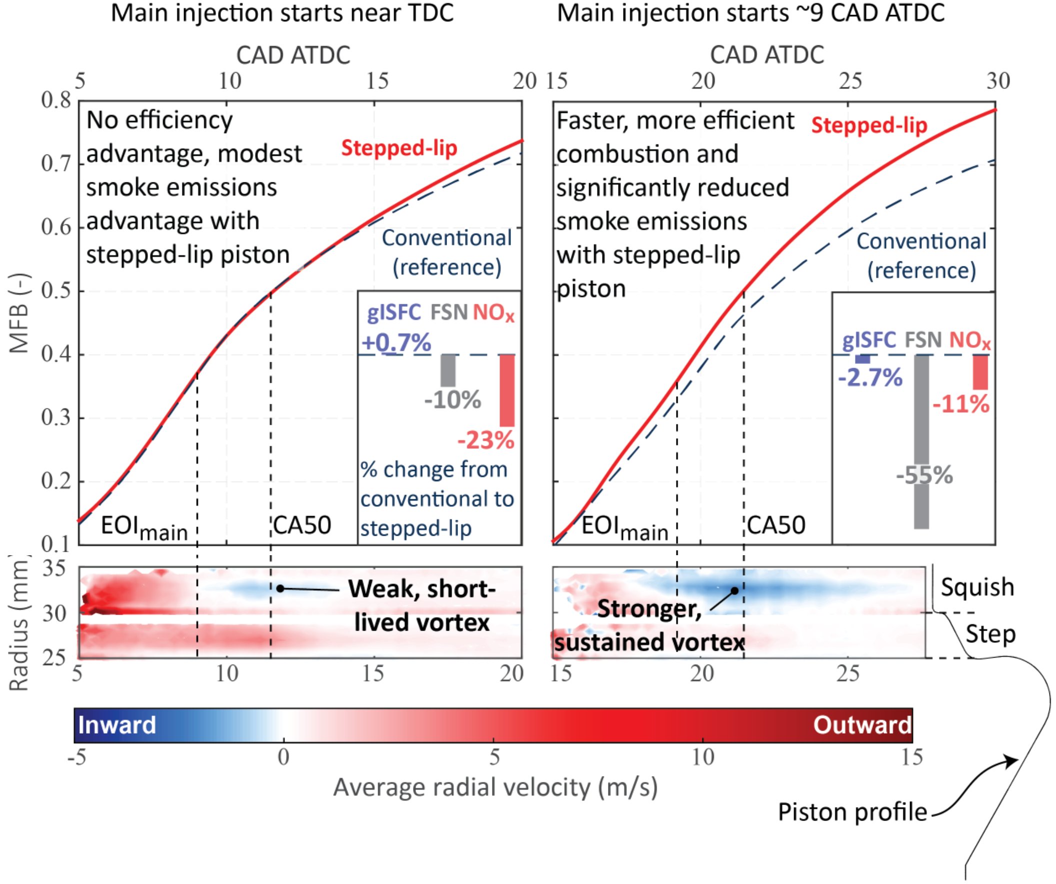
Stepped-lip piston improves thermal efficiency with near-TDC injection timing. Soot is reduced with intermediate injection timing, Busch et al., SAE 2018-01-0228.



The dimple stepped-lip (DSL) piston hypotheses (1/2)

- Experimental comparison of two piston bowls in small-bore optical diesel engine shows:
  - Stepped-lip (SL) pistons: faster, more efficient late-cycle heat release and greater soot reduction at *retarded injection timings*, but advantages disappear at near-TDC injection timings
  - Advantages correlated with strength and longevity of optically measured squish-region vortices
- Hypothesis 1: Stronger vortices at *near-TDC injection timings* may improve peak thermal efficiency and reduce soot emissions

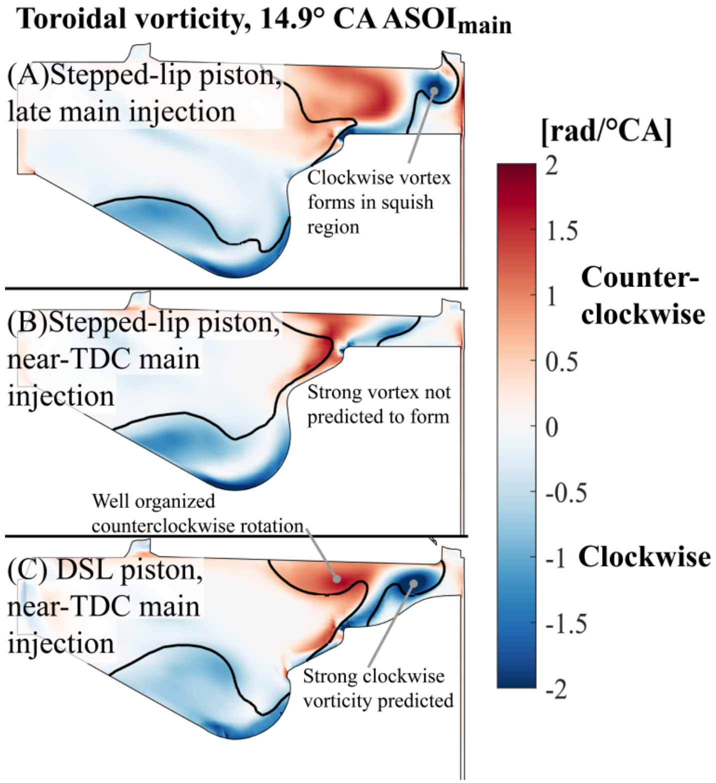
Busch et al., SAE 03-13-02-0016.



The dimple stepped-lip (DSL) piston hypotheses (2/2)

- CFD simulation study of engine operating and combustion system design parameters shows:
  - Changes in spray opening angle or intake pressure do not enhance vortex formation at near-TDC injection timings
  - Increasing squish region space by introducing *dimples* enhances vortex formation at near-TDC injection timings
- Hypothesis 2: A dimple stepped-lip (DSL) piston will promote vortex formation for near-TDC injection timings and will allow us to test the first hypothesis

Stronger squish-region vortices found in DSL piston at near-TDC injection timings, while they are weaker in the SL piston.



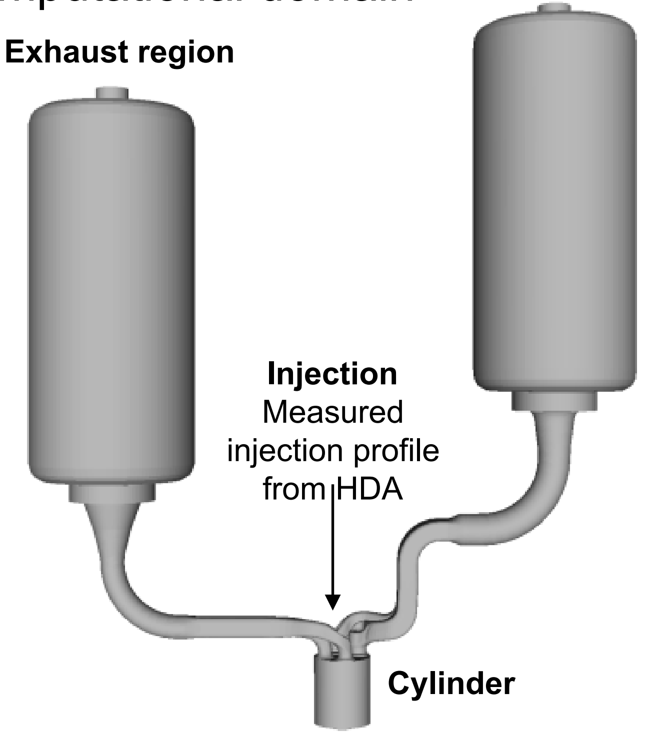
Objectives

- Analyze if DSL piston helps to enhance vortex formation in a medium-duty diesel engine at near-TDC injection timings using CFD simulations
- Study how dimple parameters affect vortex formation using CFD simulations
- Perform an experimental campaign with DSL piston to test if vortex formation helps to enhance thermal efficiency and reduce soot emissions at near-TDC injection timings

Simulation Setup – FRESCO†

Operating conditions	
Intake temperature	90°C
Engine speed	1600 rpm
Intake pressure (controlled)	137 kPa
Intake [O2]	17.963%
Intake [CO2]	2.596%
Exhaust back pressure	146 kPa
Rail pressure	1615 bar
Injection strategy	2 pilots, 1 main
Mesh	Body-fitted, unstructured hexahedral, ~ 1 million cells at BDC
Time accuracy	Hybrid 1st-order implicit (diffusion, momentum)/ explicit (advection)
Spatial accuracy	1st-order (advection), 2nd-order (diffusion)
Turbulence model	GRNG k-epsilon
Spray model	Tuned to ECN data (Spray A)
Wall model	ERC law of the wall, Han and Reitz heat transfer

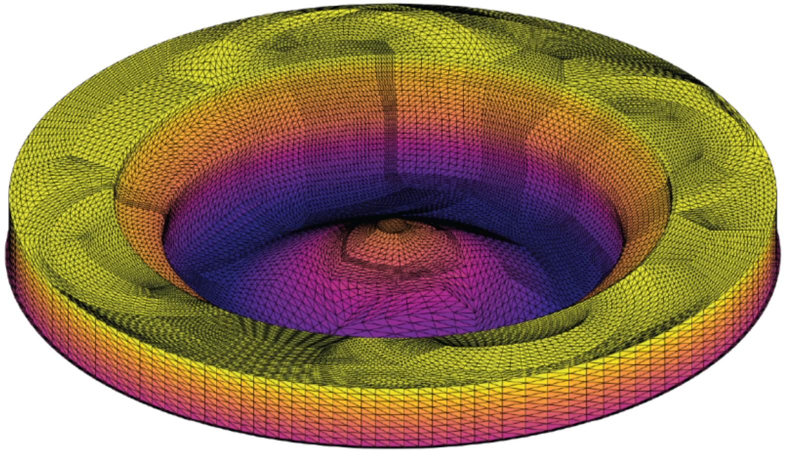
Computational domain



- Cycle 0: starts at EVO (106 CAD aTDCc)
- Cycle 1: motored cycle to establish flow
- Cycle 2: inject fuel matching

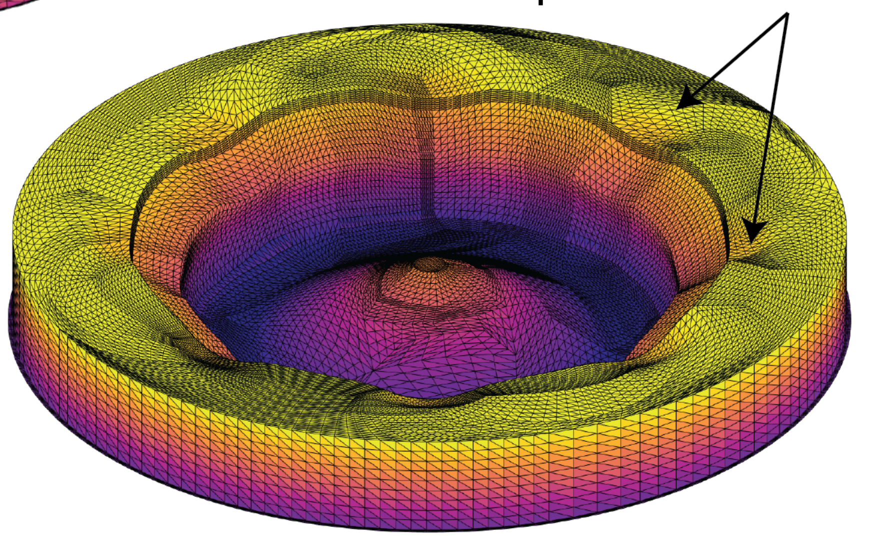
AE Congress, Detroit, MI, 2018.

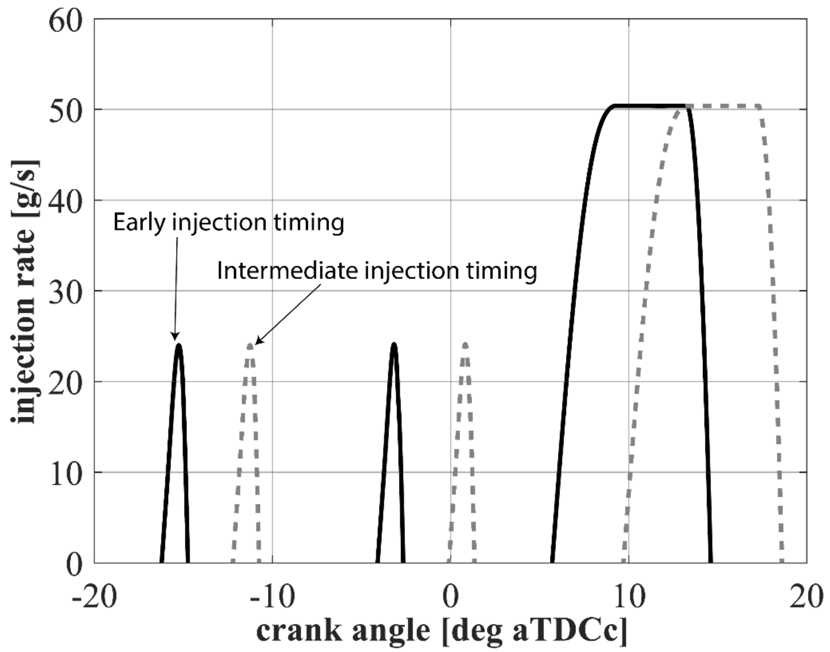
Simulation Setup, Cont’d



SL Piston

Baseline DSL piston:





Injection timing study effects on spray targeting and vortex formation

Early: 5.7 CAD

Intermediate: 9.7 CAD

Q-criteria and vorticity to identify squish-region vortices with clockwise rotation

Toroidal vorticity shows how rotational flow structures are formed

$$\omega_\theta = \frac{\left(\frac{\partial u_z}{\partial y} - \frac{\partial u_y}{\partial z}\right) sin\theta - \left(\frac{\partial u_x}{\partial z} - \frac{\partial u_z}{\partial x}\right) cos\theta}{M}$$

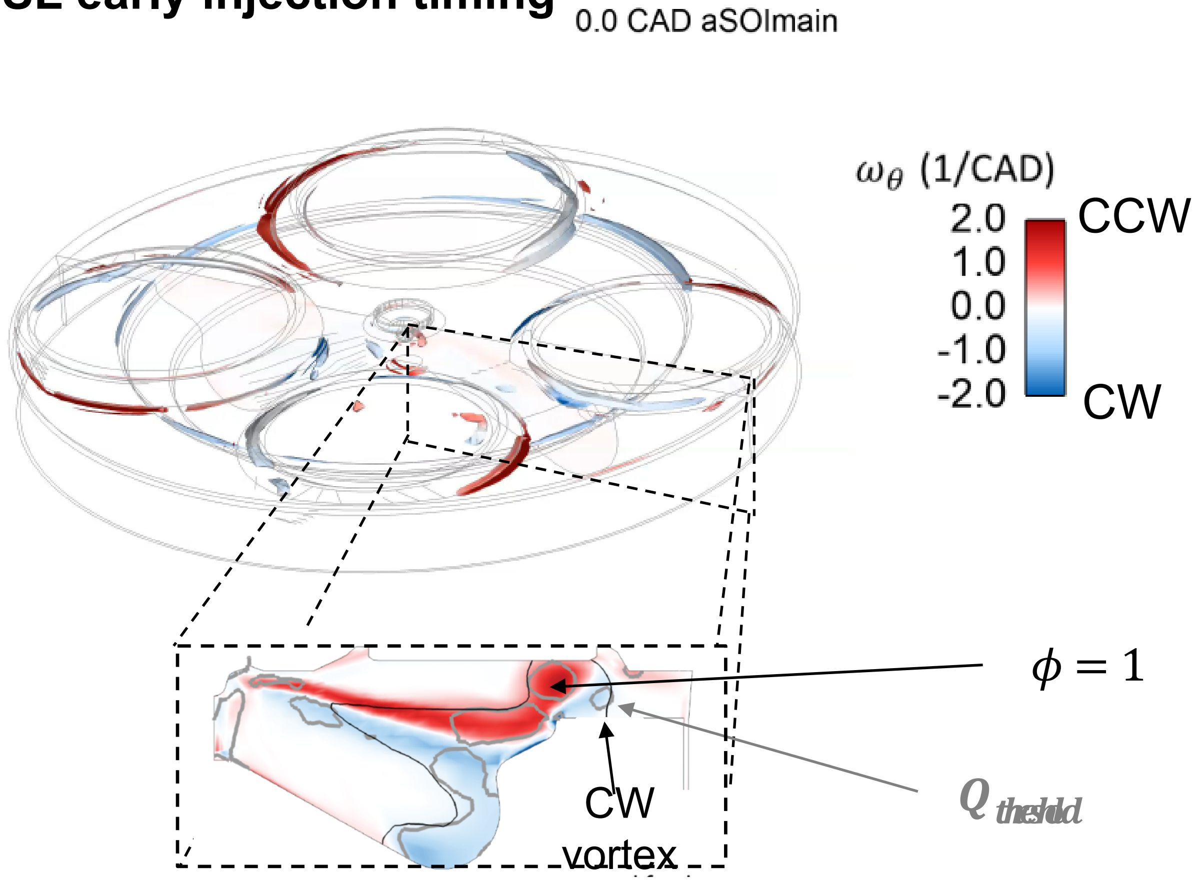
Q-criteria helps us visualize vortices

$$Q = \frac{1}{2}(|\Omega|^2 - |S|^2) > 0$$

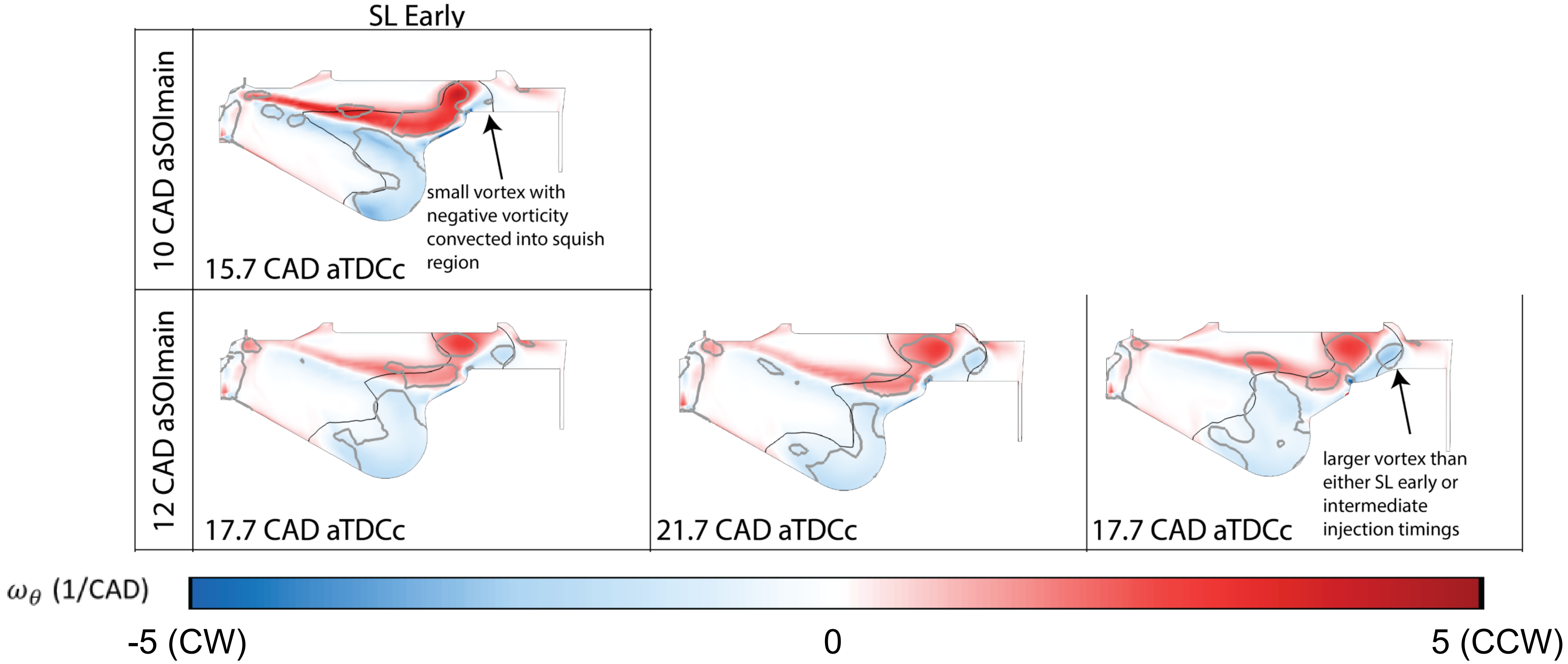
vorticit
y
Strain rate

Threshold: $Q \geq 5e6$ 1/s^2

SL early injection timing



Baseline DSL piston helps to enhance vortex formation at near-TDC injection timings



Quantifying strength and longevity of squish-region vortices with negative (CW) vorticity

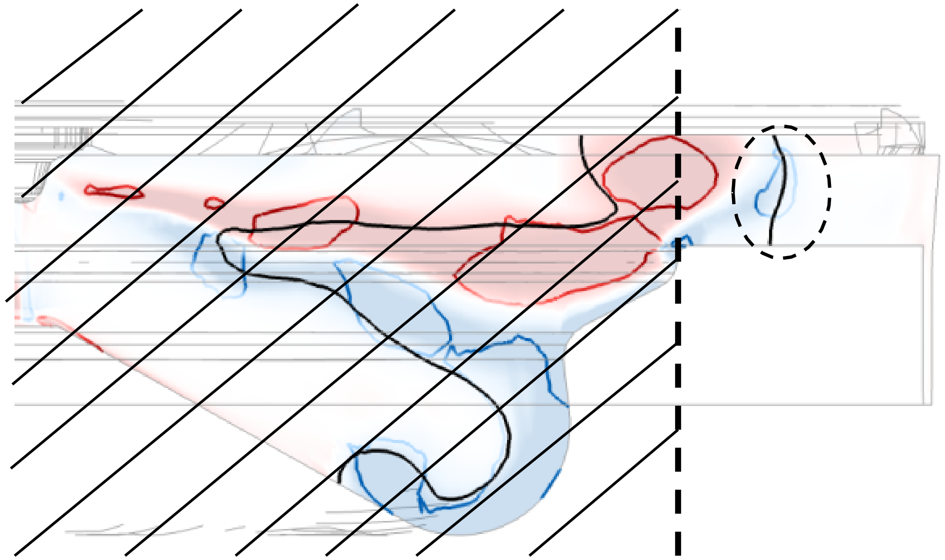
Data filtered to focus on squish-region vortices with negative vorticity

Rotational energy about the rotation center (r_c, z_c) of the vortices with max Q

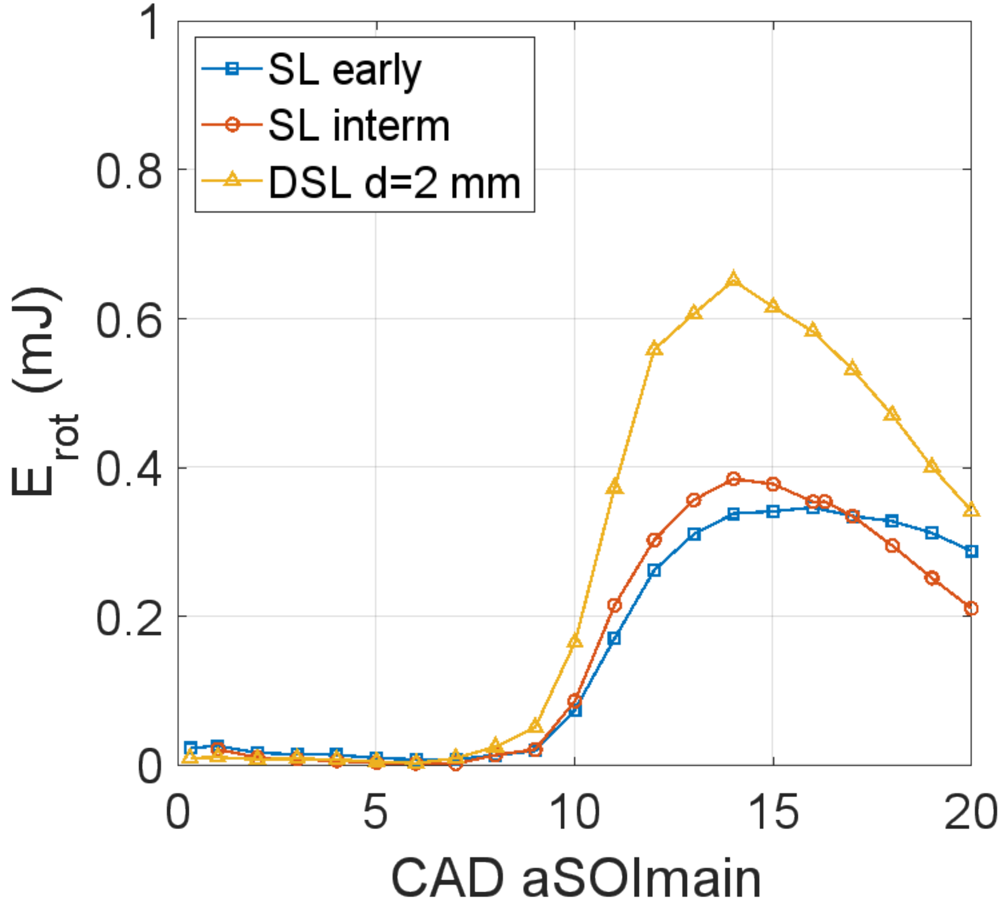
$$E_{rot} = \frac{1}{2}\sum I_i \omega_i^2 = \frac{1}{2}\sum \frac{m_i\left((z_i - z_c)u_{r,i} - (r_i - r_c)u_{z,i}\right)^2}{(z_i - z_c)^2 + (r_i - r_c)^2}$$

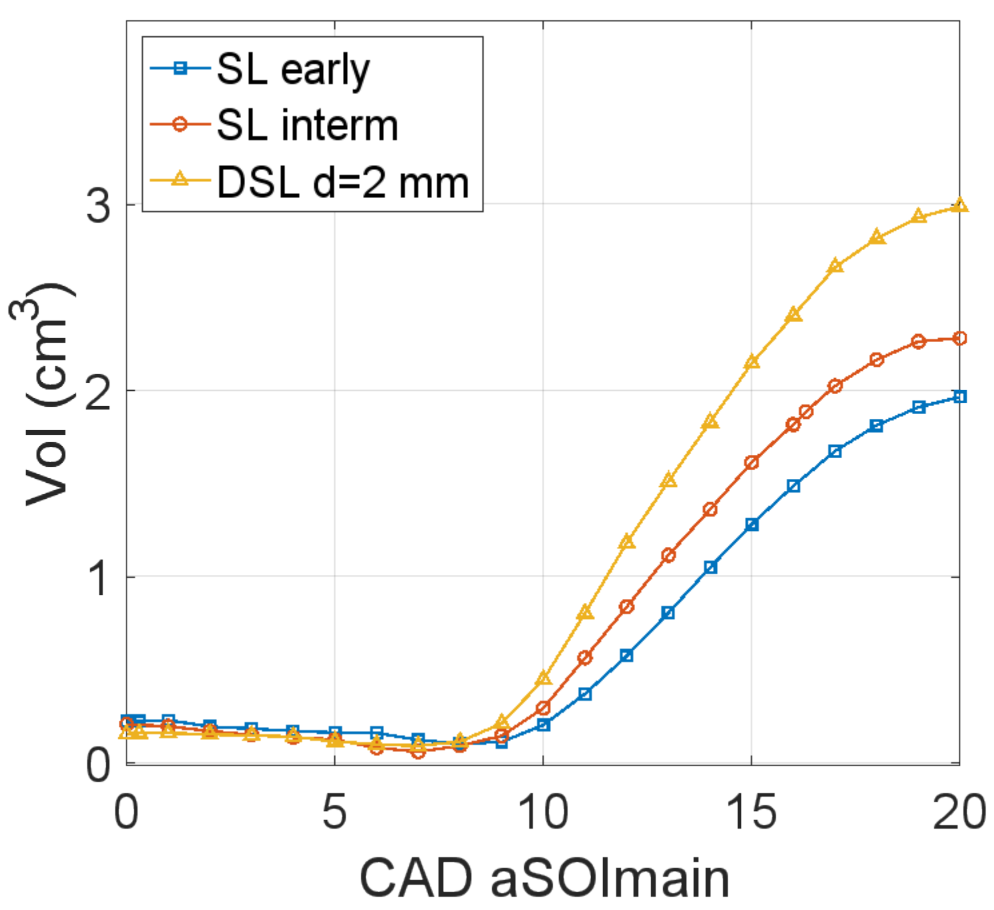
Volume of squish-region vortices

$$\mathrm{Vol} = \sum Vol_i$$



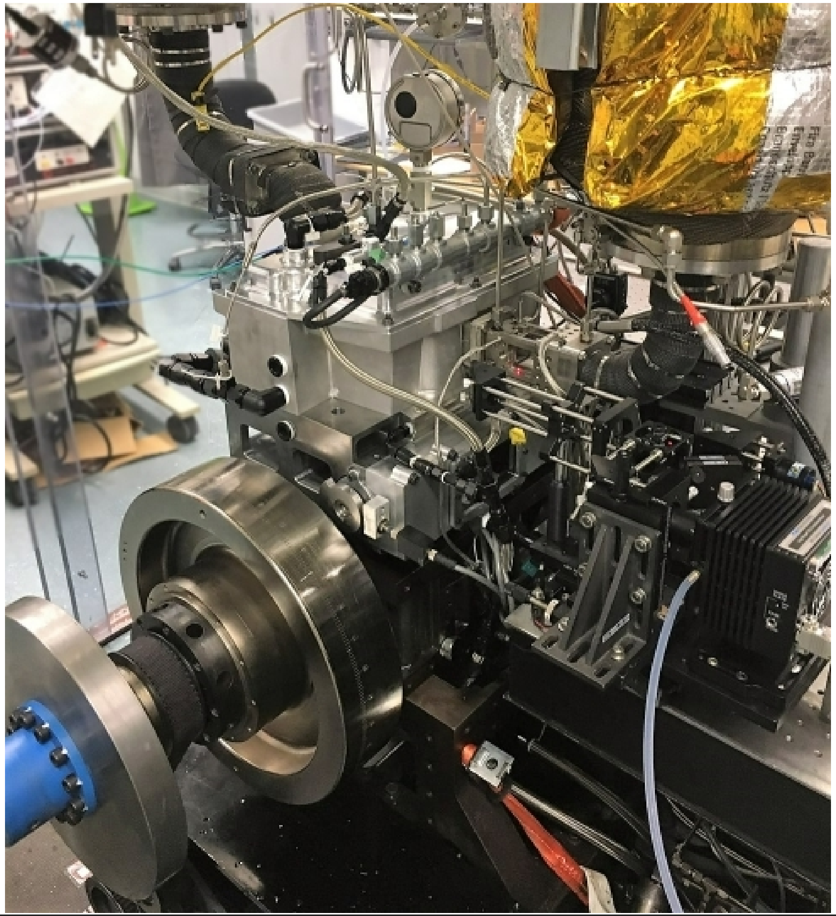
Baseline DSL bowl enhances size and rotational energy of squish-region vortices with near-TDC injection timing – supports 2nd hypothesis





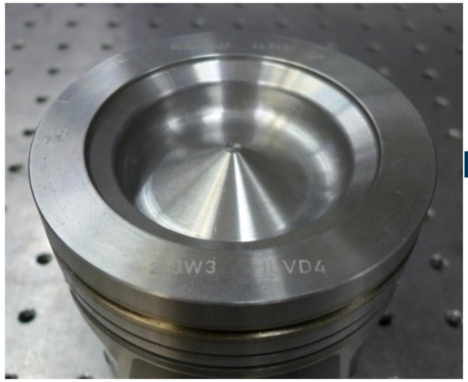
Experimental Setup

Sandia's Off-Road Diesel Research



Combustion system	Ford 6.7L Scorpion
Bore	99 mm
Stroke	108 mm
Compression ratio	16.3:1
Valves/cylinder	4
Injector	8-hole piezo

SL piston



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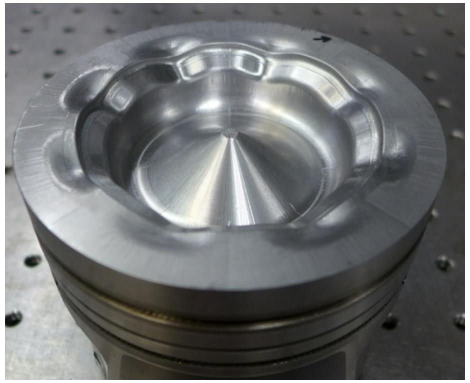
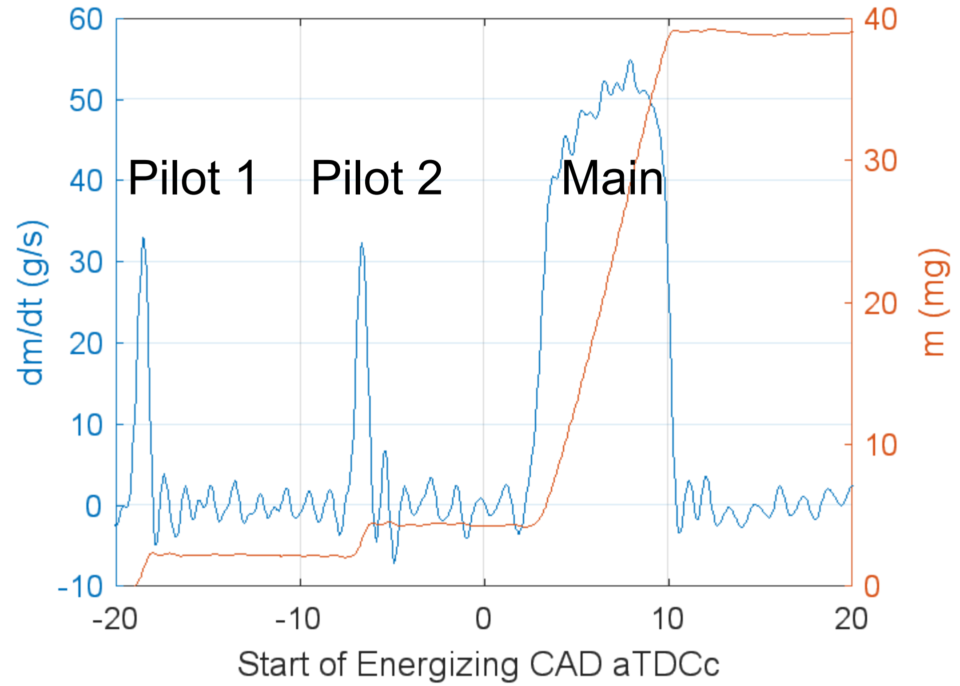
Area↓ 2.4%
Vol equal

Baseline DSL piston



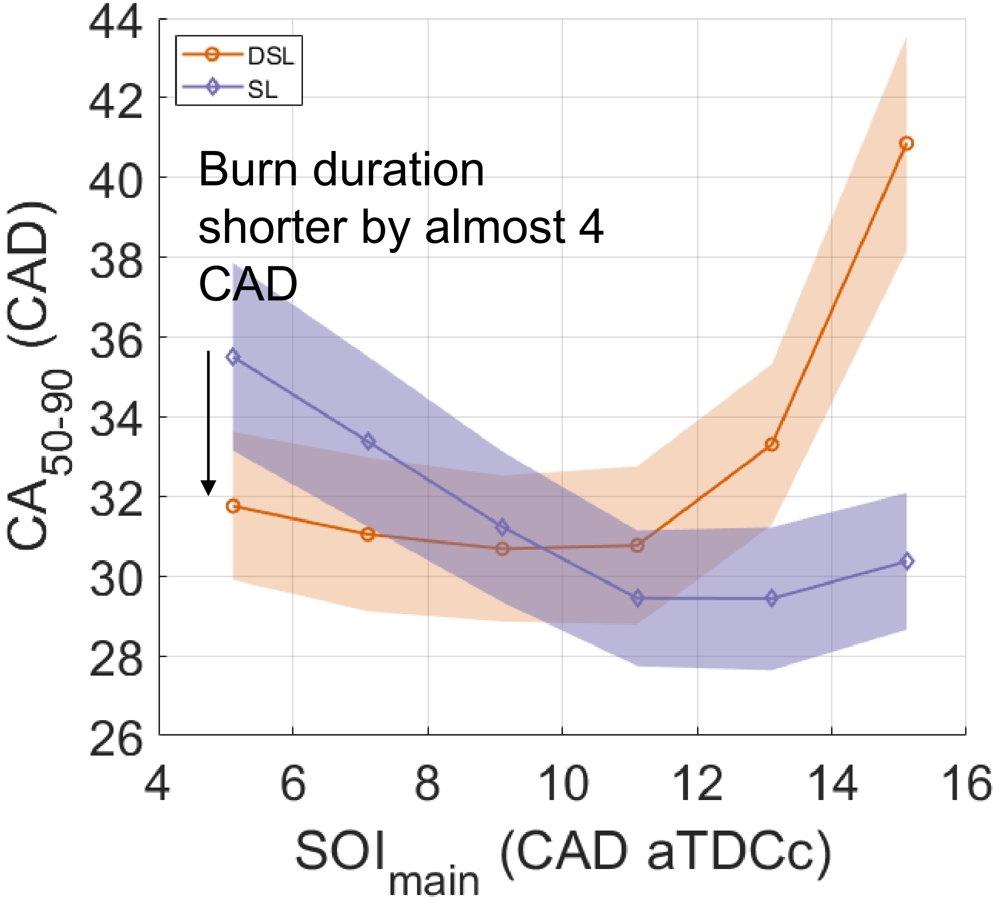
Part-Load Operating Point

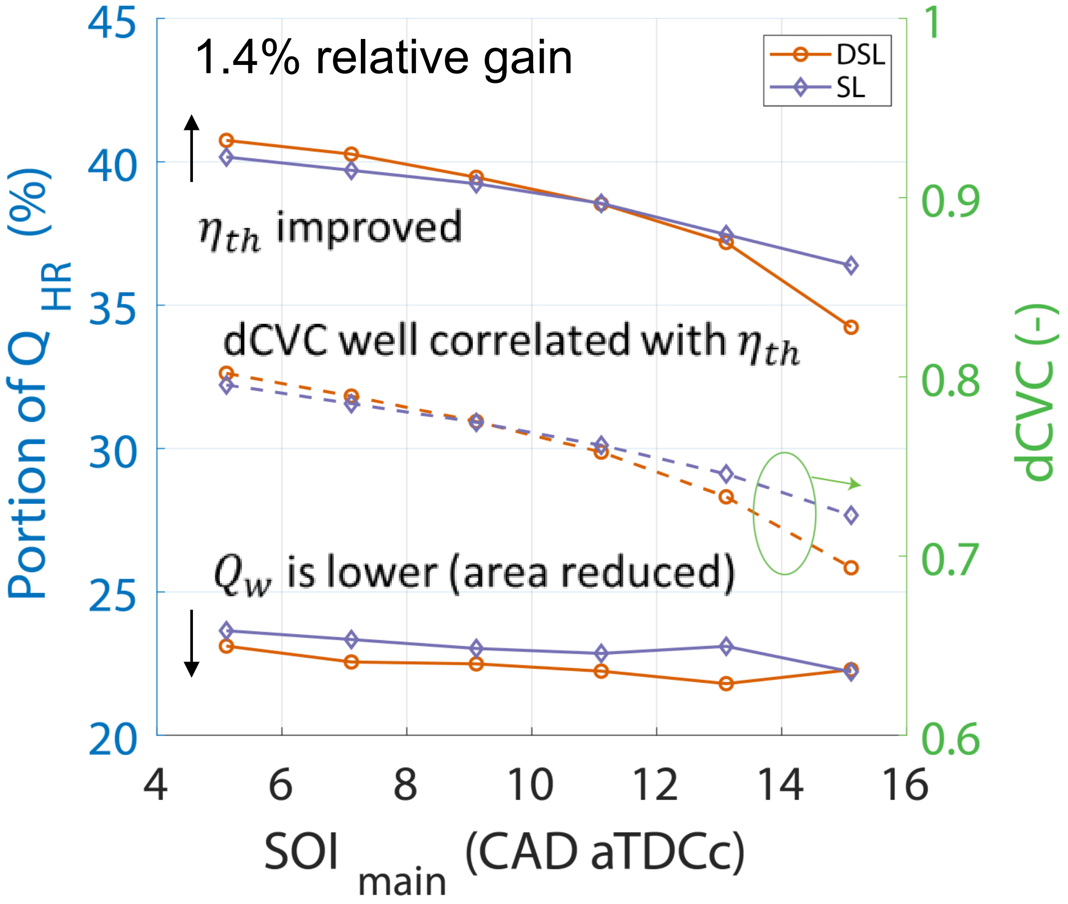
Coolant temperature	90°C
Intake temperature	44°C
Engine speed	1600 rpm
IMEPn	8.55 bar
Intake flow rate	14.9 g/s
Intake pressure (not controlled)	137 kPa
Simulated EGR rate	20%
Intake [O2]	17.963%
Intake [CO2]	2.596%
Exhaust back pressure	146 kPa
Exhaust diluent flow rate	10 g/s
Rail pressure	1615 bar
Injection strategy	2 pilots, 1 main
Fuel	Cert diesel (CN 46)



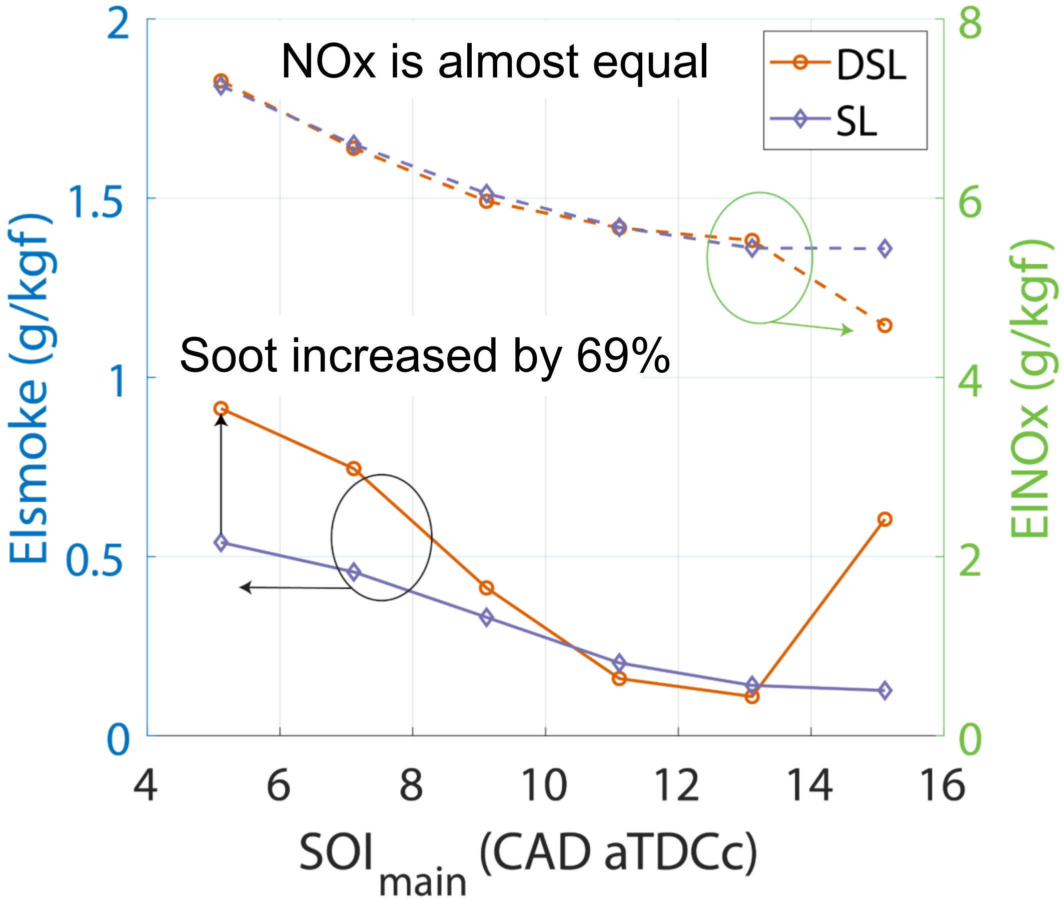
SOI_{main} sweep 5.1: 2 : 15.1 CAD
$duration_{main}$ is load-adjusted

The DSL piston reduces burn duration and improves thermal efficiency with early-injection timing, which is correlated with the stronger squish-region vortices



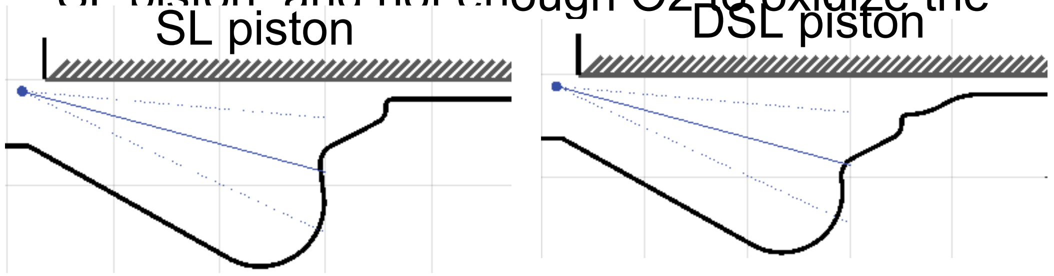


Despite improvements in thermal efficiency, soot emissions increased



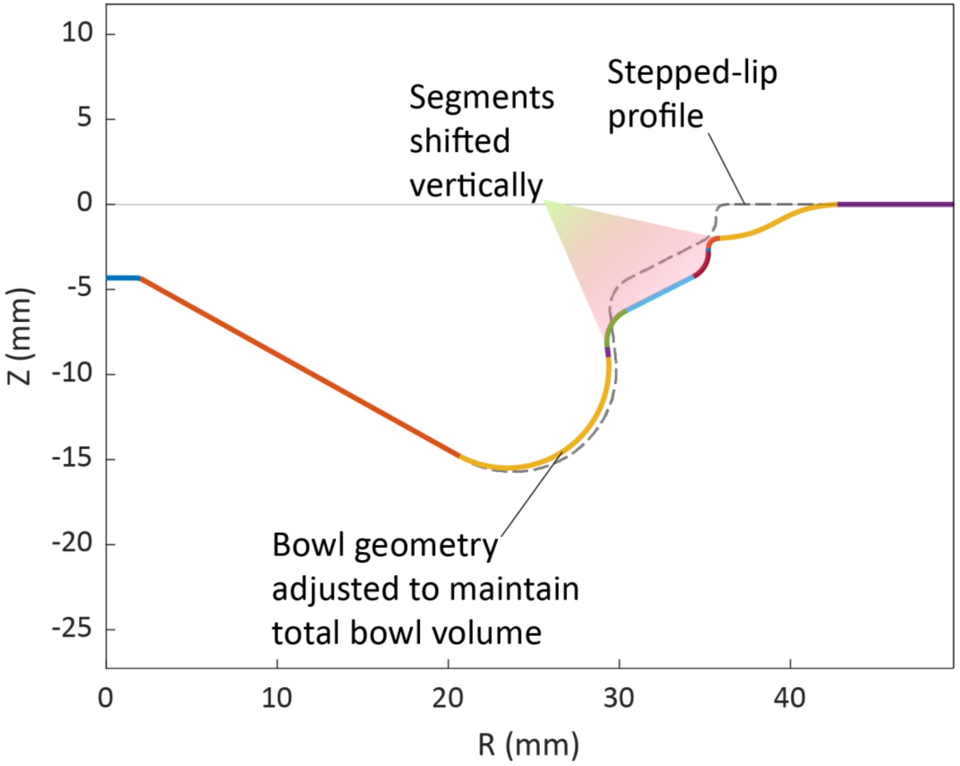
Enhanced squish-region vortices tend to improve air utilization, therefore, soot should reduce.

One possibility: change in fuel splitting in DSL piston, with more fuel directed upwards than SL piston, and not enough O2 to oxidize the



SL piston spray targeting is lower in the bowl, while in DSL piston, it’s more evenly distributed.

Can we design a better DSL bowl using CFD? Dimple parameter design sensitivity study

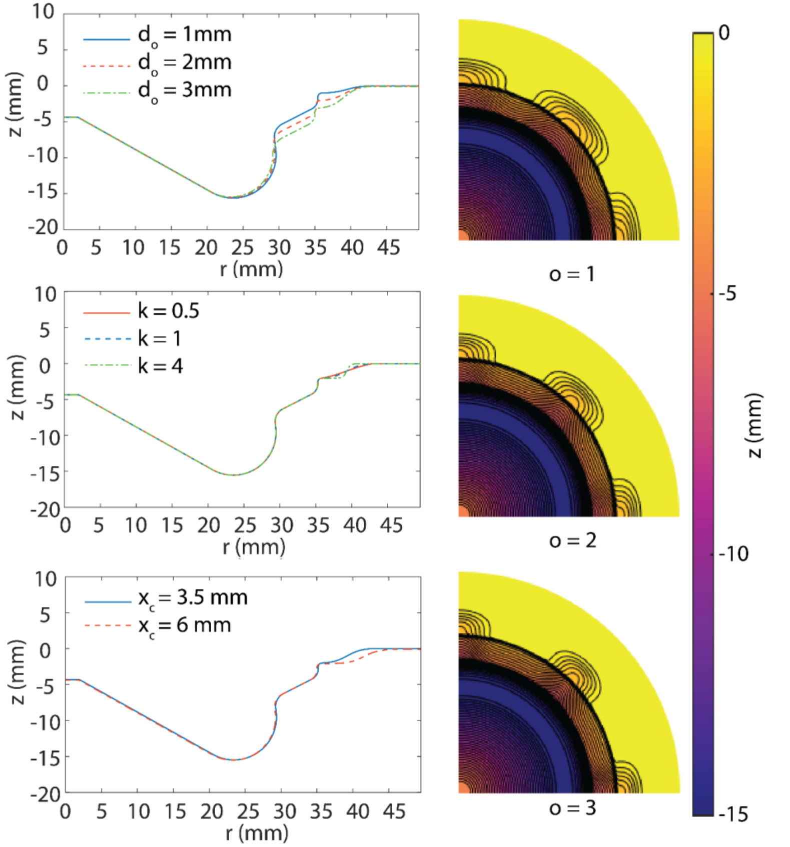


Dimple depth d

Radial steepness

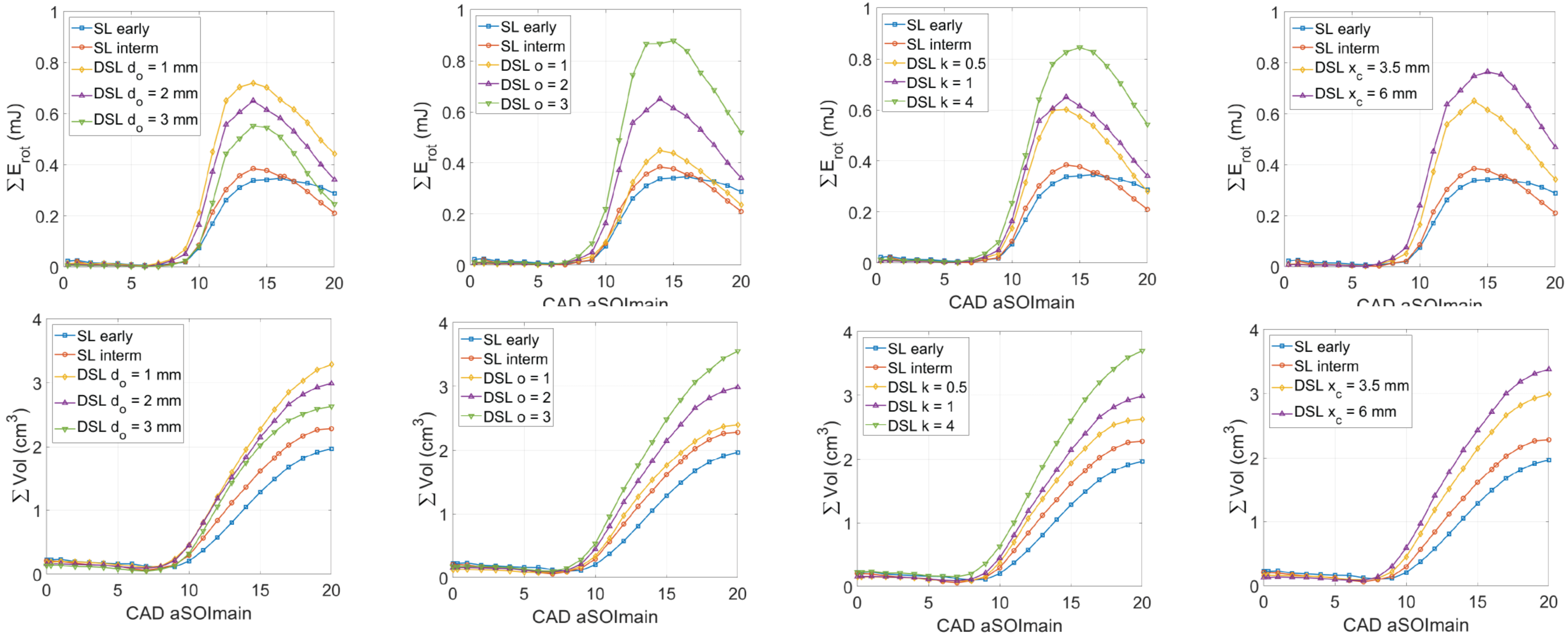
Radial extent x_c

Azimuthal order o

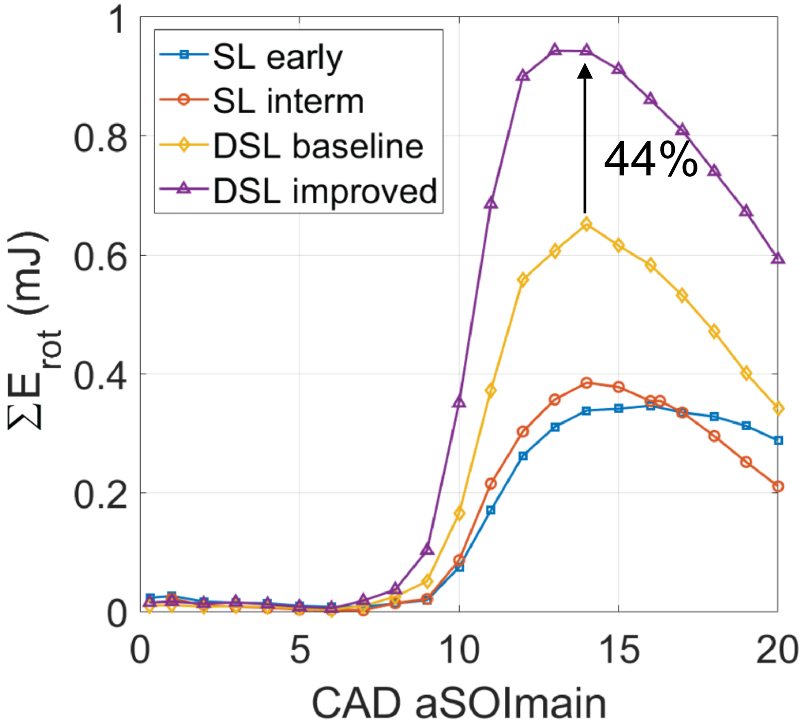


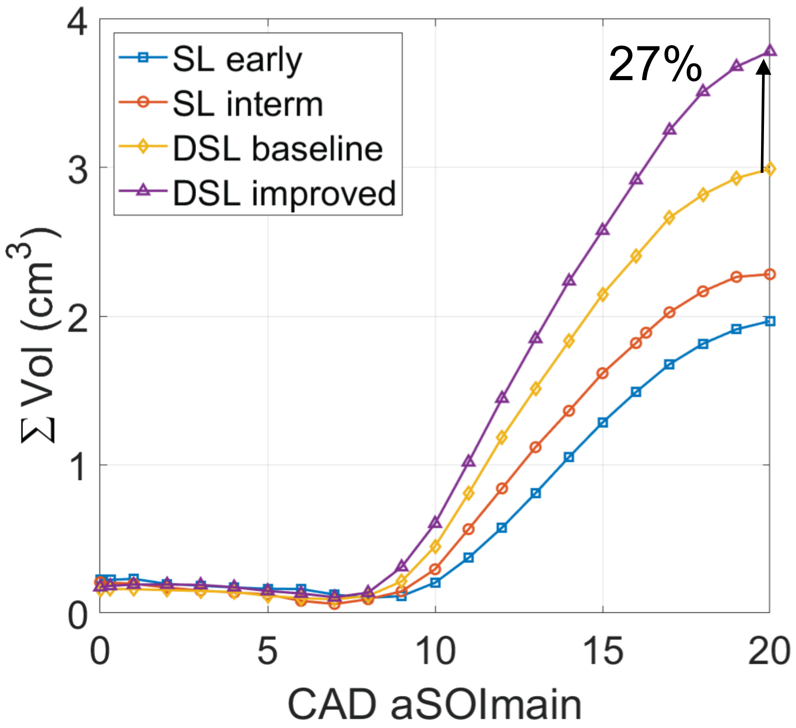
To produce stronger and larger vortices at near-TDC injection timing, dimples should be shallower, with sharper features, and placed closer to the liner

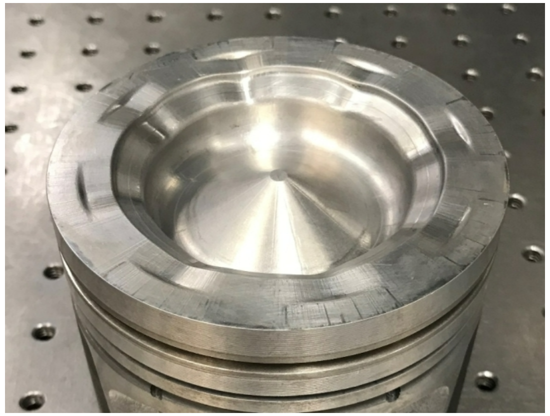
Dimple depth d | Azimuthal order o | Radial steepness k | Radial extent x_c



Design sensitivity study reveals a DSL bowl that maximizes rotational energy at near-TDC injection timings







1.4% reduction in area vs. SL piston

Bowl volume constant

Conclusions

- CFD simulations predict that spray-wall interactions in the DSL piston generate larger, more energetic vortices in the squish region than those predicted with the production SL piston
- Experiments with the baseline DSL piston show improvements in thermal efficiency, shorter burn duration, and enhanced degree of constant volume combustion, but increased soot levels and no penalty in NOx emissions compared to the SL piston
- CFD design sensitivity study shows that, to produce stronger and larger vortices at near-TDC injection timings, DSL pistons should have shallower dimples, steeper curvatures, and dimples further into the squish region
- The sensitivity study led to the design of an improved bowl with 44% increased rotational energy and 27% larger squish-region vortices compared to the baseline DSL bowl

Acknowledgment

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Speaker information

Thank you

Angela Wu

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Postdoctoral Appointee, CFD and experimental studies to optimize diesel piston design; 1-D spray modeling development for improved boundary condition

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