SAND2019-4437PE

Diesel piston bowl geometry: an enabler for continued efficiency improvements?

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April 25, 2019

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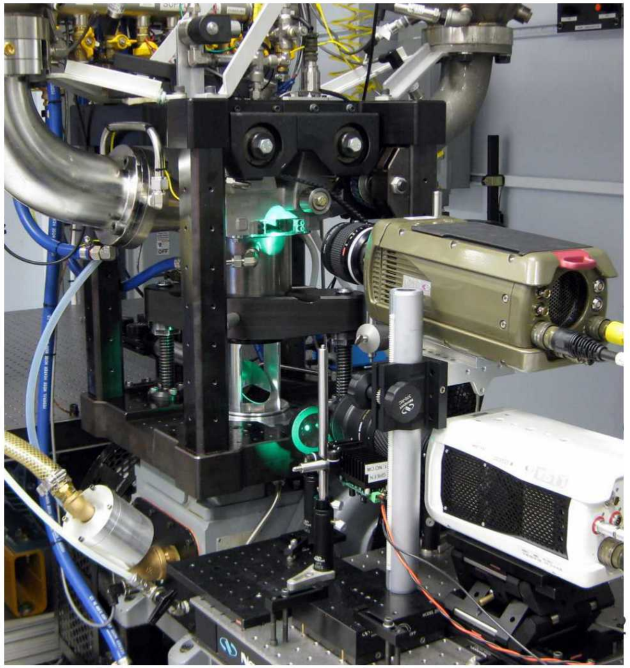
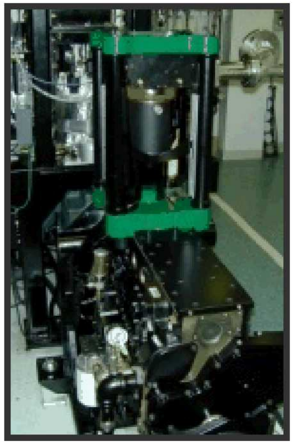
Sandia's Engine Combustion Research Mission

- Provide the combustion and emission knowledge-base needed by industry to develop high-efficiency, clean internal combustion engines adapted to future fuels -- research spans needs from 5 to 20+ years out

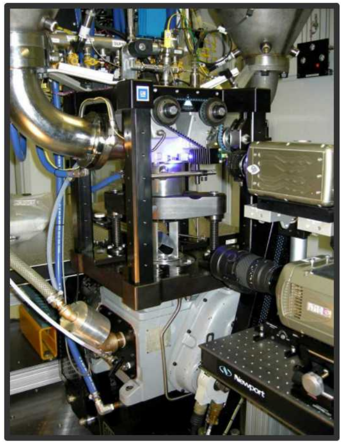
- >30 staff, technologists, post docs, and visiting researchers
  - world experts, selected for strong fundamentals
  - staff deeply engaged in leadership roles in the field



Current laboratories/projects (research portfolio)

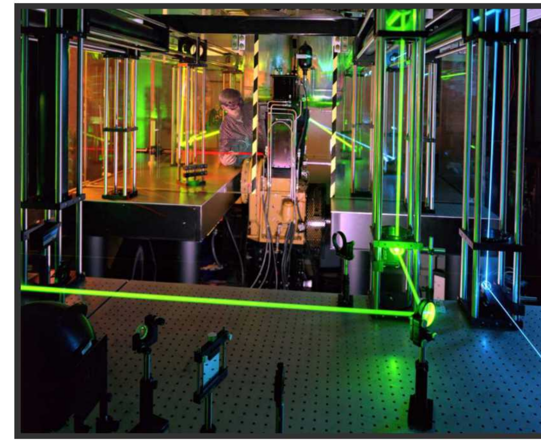


Low-temperature gasoline combustion
PI – John Dec

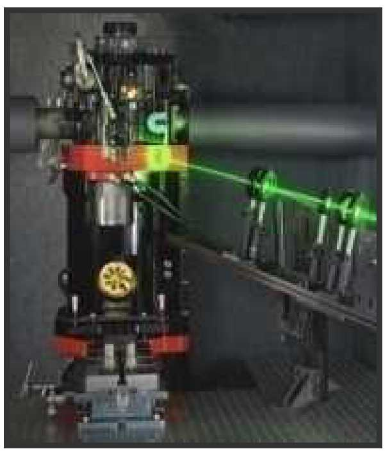


Alternative fuels – light-duty DISI
PI – Magnus Sjoberg

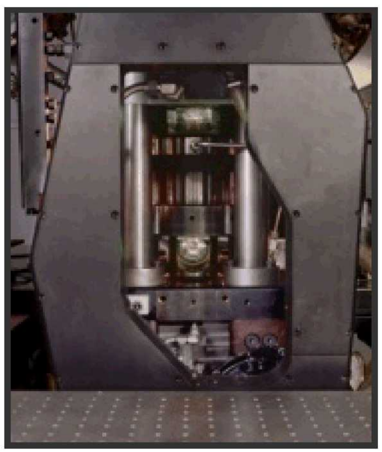
SI ignition & combustion fundamentals
PI –Isaac Ekoto



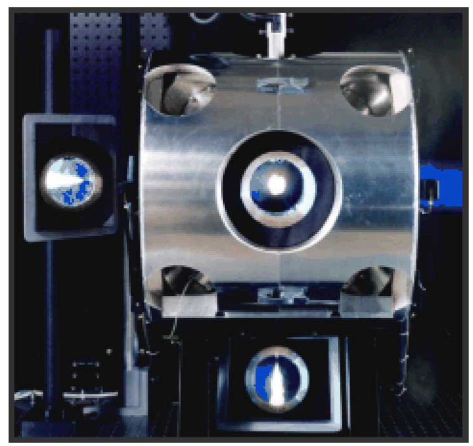
Alternative fuels – Heavy-duty CI:
PI – Chuck Mueller



HD Diesel/LTC diesel combustion
PI – Mark Musculus



MD diesel combustion
PI – Steve Busch



Fuel sprays and soot:
PIs – Lyle Pickett and Scott Skeen

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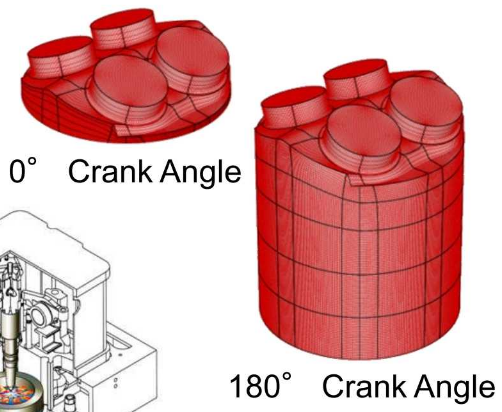
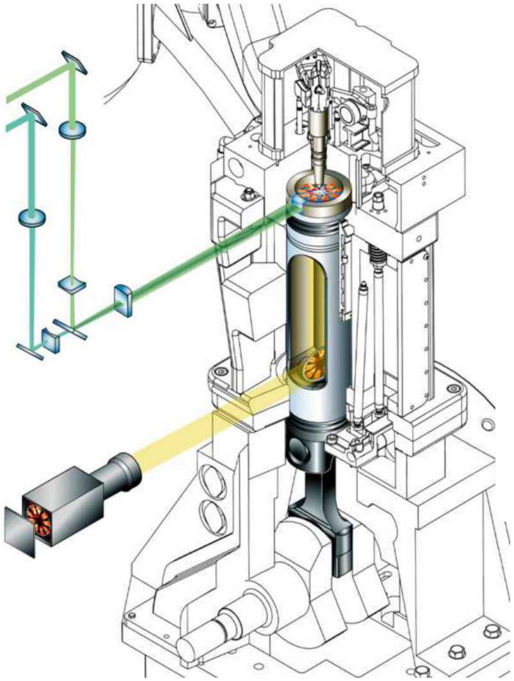
Research approach - closely coupled experiments and simulation

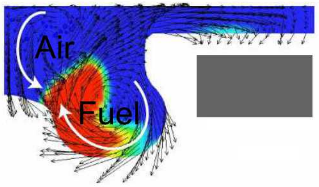
- Optical combustion diagnostics
- Optically accessible engines – realistic operating conditions
- Simulation
  - CFD collaboration with partners
  - High-fidelity simulation tools (Large Eddy Simulation – LES)

In-depth analysis of the controlling physical/chemical processes

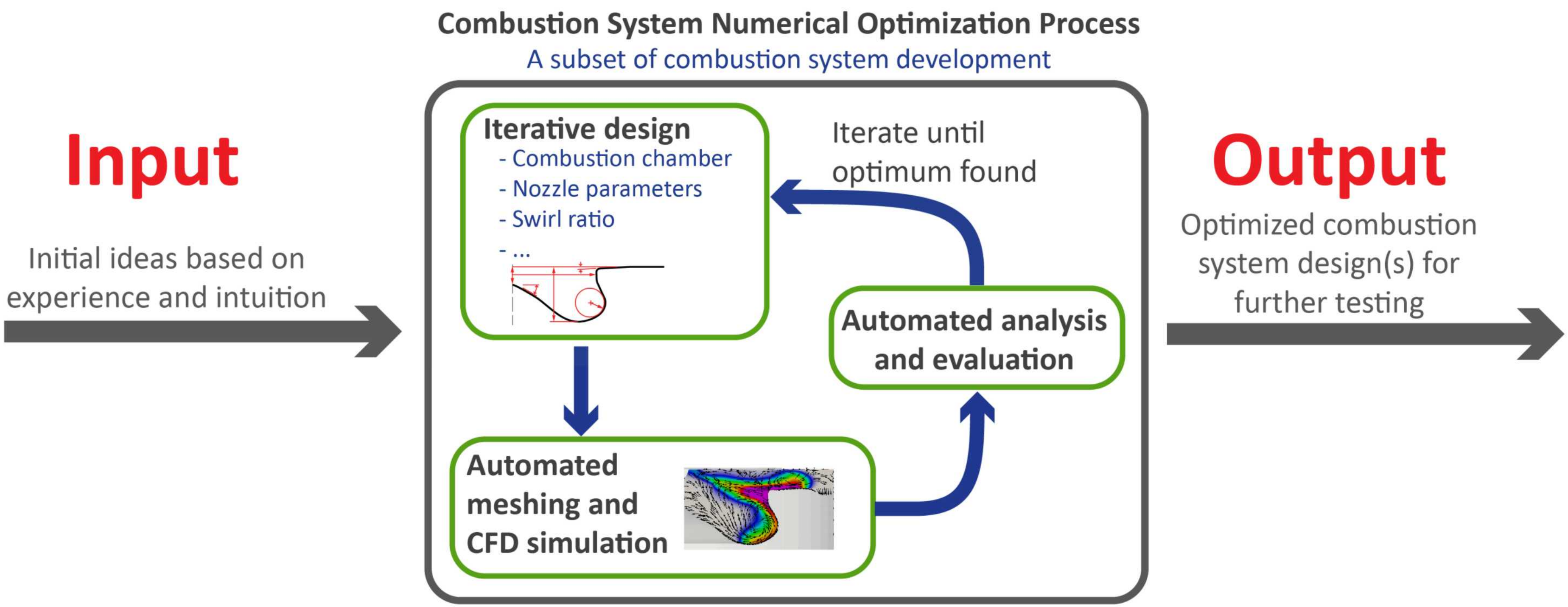
Time varying LES Grids
3-million cells, 137 blocks







How can diesel combustion system designs be improved?

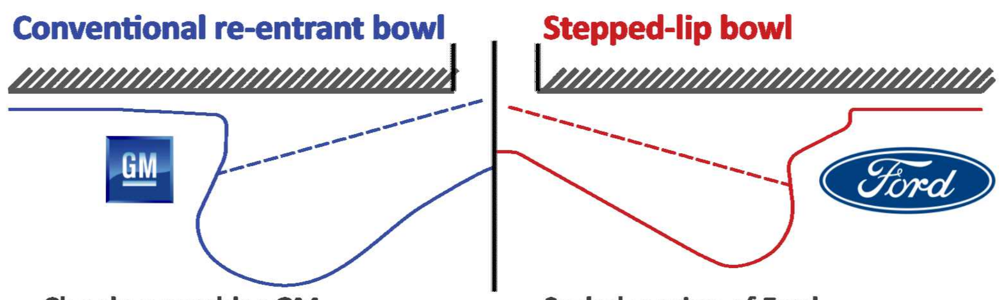


Outline: piston bowl geometry study

- Research approach
- Experimental engine and operating point
- Results and analyses
  - Thermodynamic experiments
  - Optical experiments
  - Numerical simulations
- Summary
- Outlook

Research approach: piston bowl geometry study

- Adapt two piston geometries from production engines that represent two competing approaches to diesel combustion system design



- Closely resembles GM 1.9L bowl geometry
- Spray targeting based on GM guidance

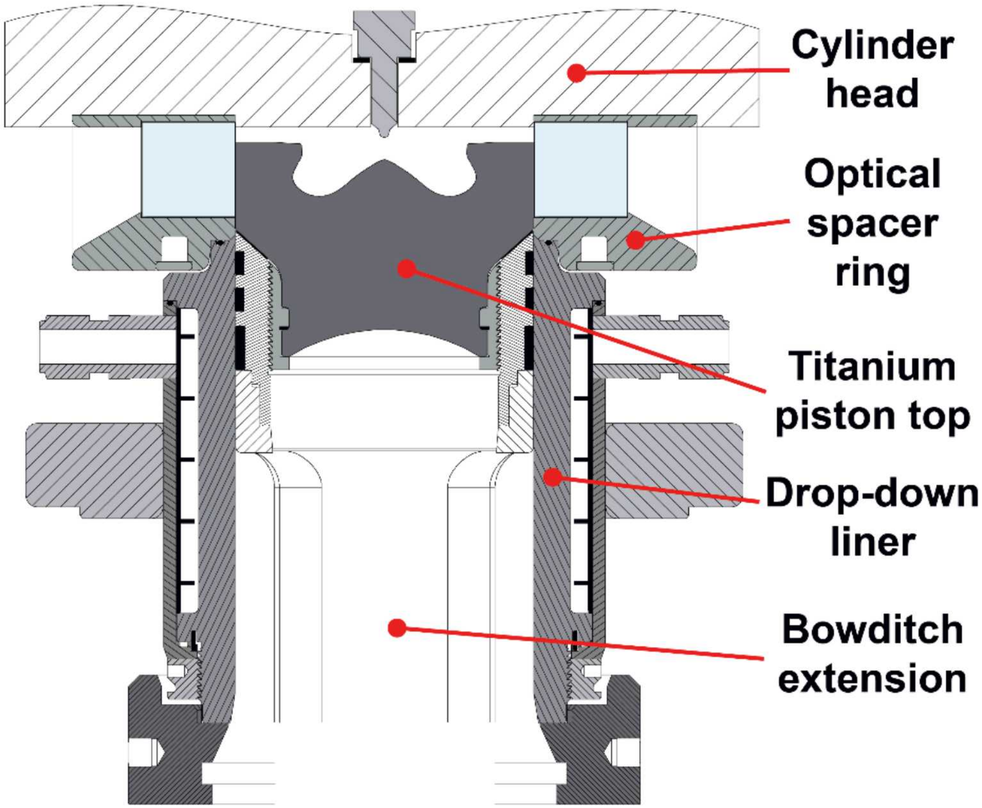
- Scaled version of Ford 6.7L bowl geometry
- Spray targeting based on Ford guidance

- In-depth study of a single operating point to understand bowl geometry impacts on efficiency and emissions

- Experiments: thermodynamic and optical

- 3D-CFD simulations: in-depth analyses

Sandia's small-bore diesel research engine (2005 – March 2019)

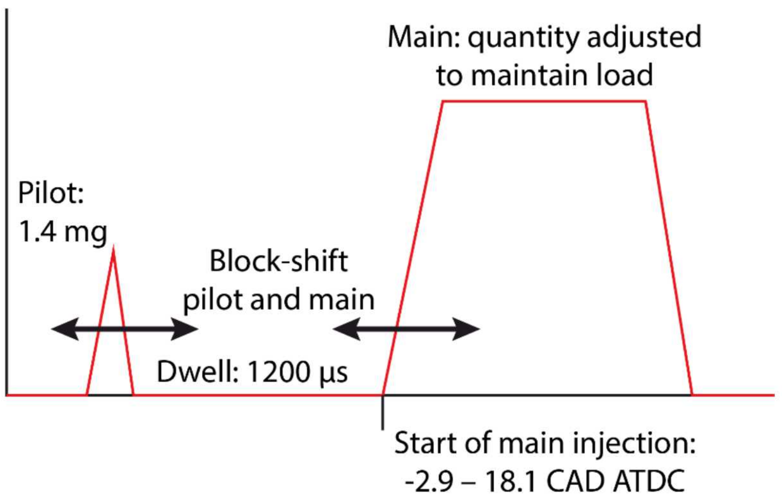


Thermal engine configuration shown. Fused silica piston crown windows are used for optical experiments.

Bore	82.0 mm
Stroke	90.4 mm
Displacement volume	0.477 L
Geometric compression ratio	15.8:1
Injector nozzle holes x diameter	7 x 139 µm
Nozzle hole conicity (k_s)	1.5
Injector included angle	149°

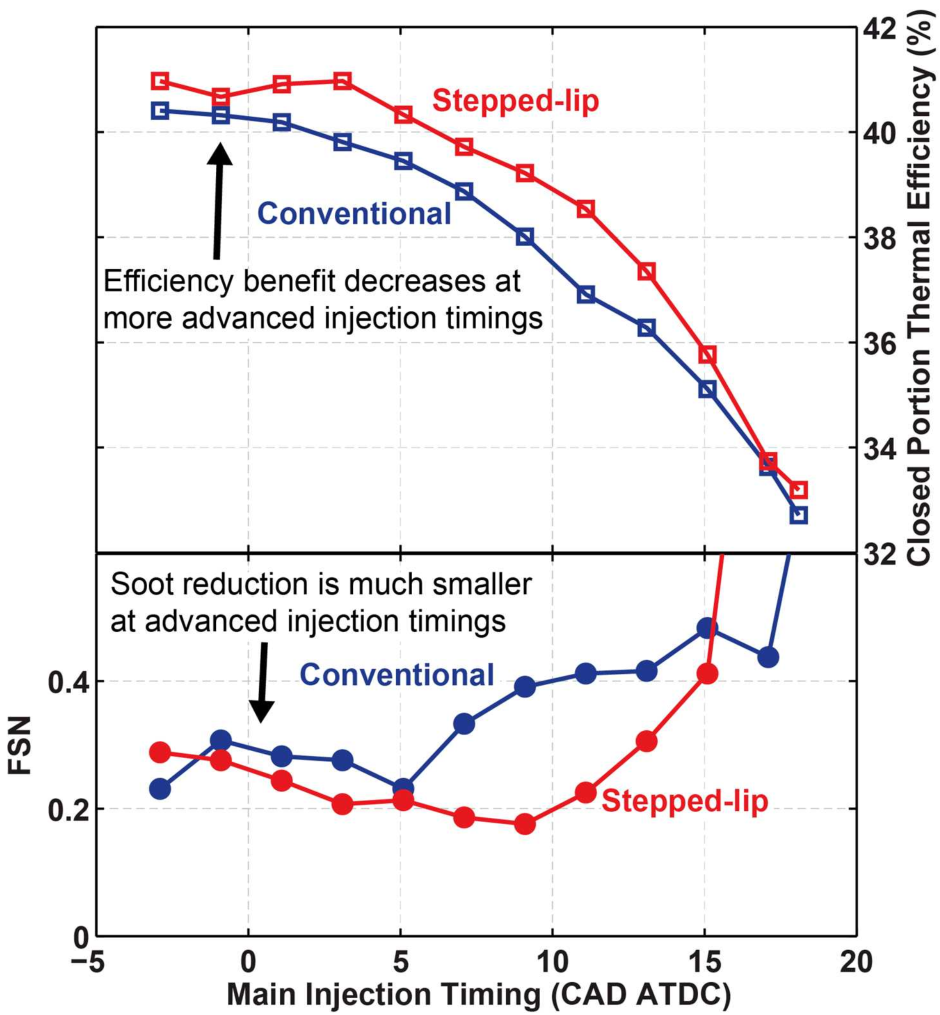
Engine operation (skip-fired)

Engine speed	1500 rpm
Swirl ratio	2.2
Injection pressure	800 bar
Intake pressure	1.5 bar
EGR rate (simulated)	10.3% (7% EGR + 3.3% residual fraction)
Injection strategy	Pilot-main
Pilot quantity	1.4 mg
Pilot-main dwell	1200 µs
Main quantity	Adjusted to maintain load
Start of main injection	-2.9 - 18.1 CAD ATDC
$IMEP_g$	9 bar



Engine performance and emissions

- The stepped-lip piston results in improved efficiency, but benefits decrease as injection timing is advanced
- Soot emissions can be significantly reduced with the stepped-lip piston, but benefits are only realized for late injection timings
- **Hypothesis:** if we can understand the efficiency and emissions advantages of the stepped-lip combustion system, then we will be able to improve its behavior for near-TDC injection timings
    - What is responsible for the efficiency improvement?



The literature suggests several possible mechanisms for improved efficiency with stepped-lip pistons

	Change wall heat-loss			Change combustion duration
	Surface area/volume	Squish/swirl flow velocities	Spray-wall interactions	Mixing-controlled heat release
Stepped-lip advantage	Smaller	Possibly reduced	Unknown	Faster

First-law analysis: is the efficiency improvement the result of changes to wall heat loss, or to changing combustion duration?

Thermodynamic analysis tools

Heat release analysis

- First-law, ideal-gas analysis

$$\frac{dQ_{hr}}{d\theta} = \frac{dQ_{wall}}{d\theta} + \frac{\gamma P \frac{dV}{d\theta} + V \frac{dP}{d\theta}}{\gamma - 1}$$

- Wall heat-loss computed with Woschni's correlation
- Analysis of closed portion of cycle (IVC – EVO)

Comparison metrics (cycle-resolved)

- Thermal efficiency:

$$\eta_{th} = \frac{\int_{V_{IVC}}^{V_{EVO}} P dV}{Q_{hr,total}}$$

- Normalized wall heat-loss:

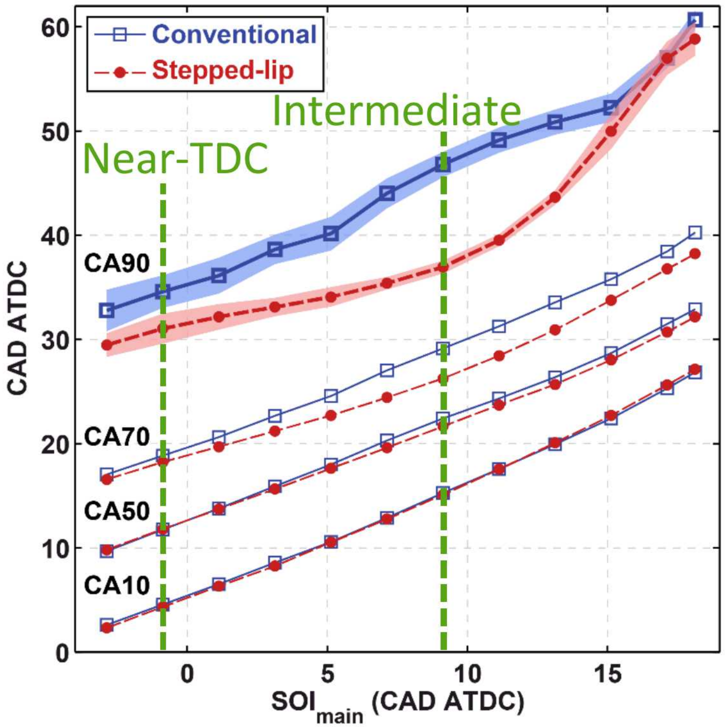
$$Q_w^* = \frac{\int_{IVC}^{EVO} \frac{dQ_w}{d\theta} d\theta}{Q_{hr,total}}$$

- Degree of constant volume combustion:

$$dCVC = \frac{1}{\eta_{otto} Q_{hr,total}} \int \left(1 - \left(\frac{V_d + V_c}{V(\theta)}\right)^{1-\gamma} \frac{dQ_{hr}}{d\theta}\right)$$

Bowl geometry effect on combustion phasing for injection timing sweep

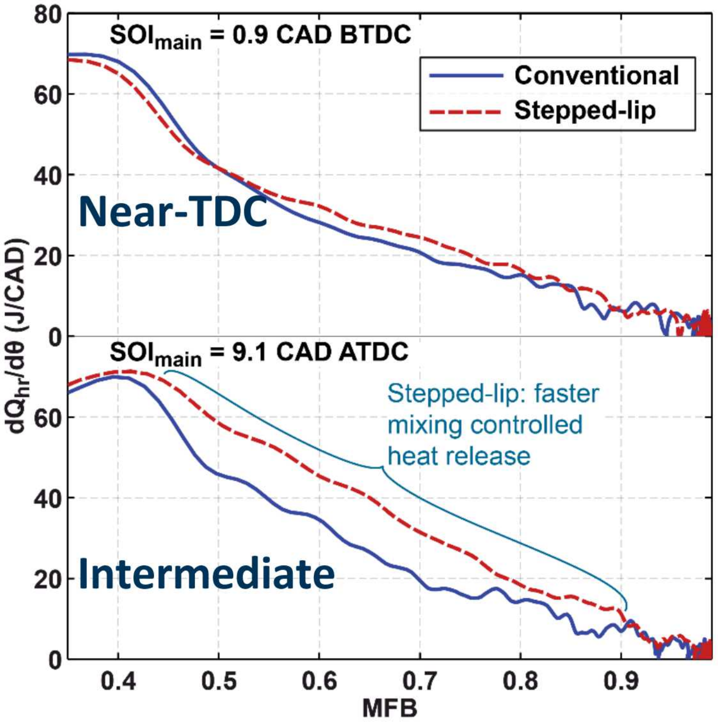
- Combustion phasing retards with injection timing
- Bowl geometry has little effect before CA50
- After CA50, heat release is often faster with the stepped-lip piston
  - This effect depends on injection timing
  - Focus on two injection timings



Bowl geometry effect on mixing-controlled heat release rates

- Top plot: mixing-controlled heat-release rates are modestly increased with the stepped-lip piston after CA50

- Bottom plot: significant increase in heat-release rates with stepped-lip piston
  - After CA50
  - After heat-release rate reaches its maximum

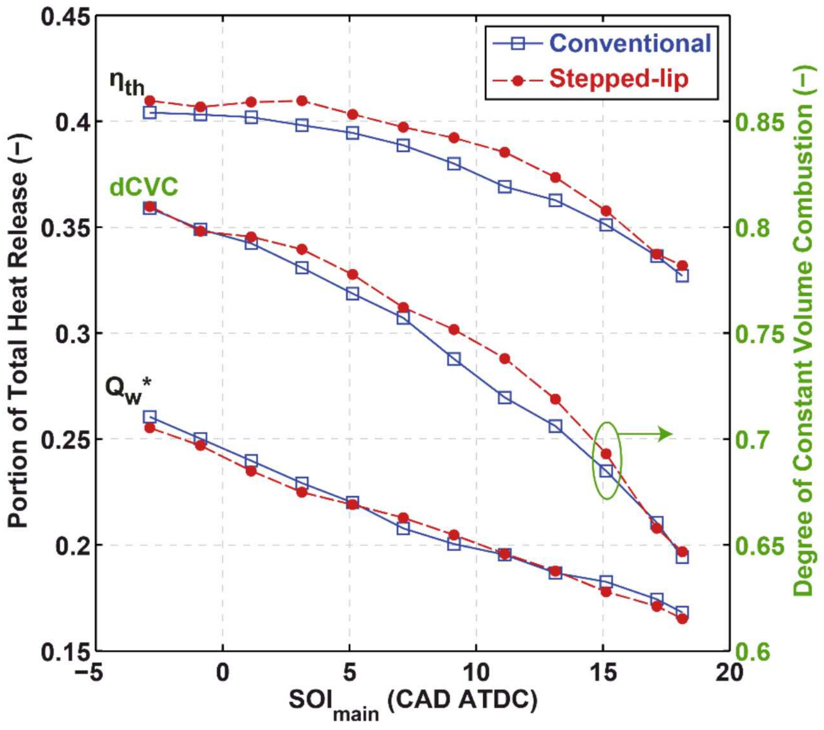


Bowl geometry effect on thermal efficiency, wall heat loss, and dCVC

- Thermal efficiency improves with the stepped-lip piston for intermediate injection timings

- Normalized wall heat loss may increase or decrease, depending on injection timing

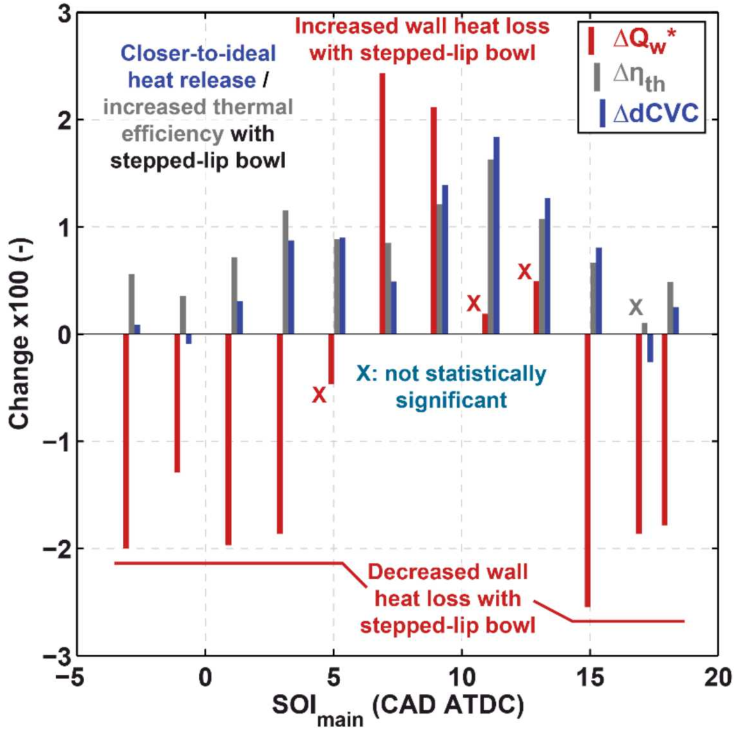
- The degree of constant volume combustion is higher with the stepped-lip piston for intermediate injection timings



Changes in thermal efficiency with stepped-lip piston – wall heat loss or faster combustion?

- Efficiency improvements do not appear to correlate with changes in wall heat-loss
  - Statistical analysis confirms that the computed changes in wall heat loss are not a significant contributor to observed changes in efficiency

- The change in the degree of constant volume combustion correlates well with the improvement in efficiency



Recap: thermodynamic analyses

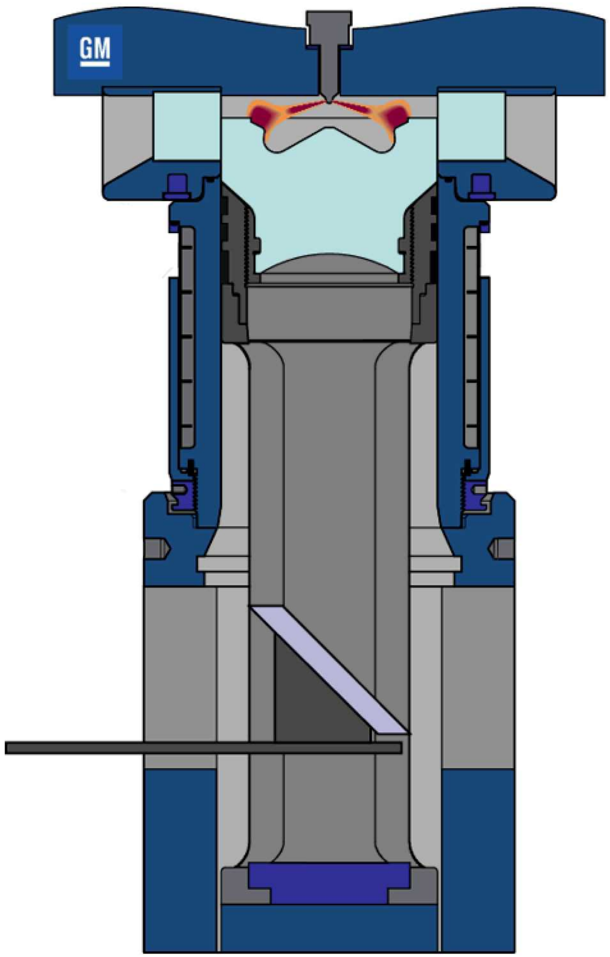
- The efficiency advantages of the stepped-lip piston are associated with faster combustion

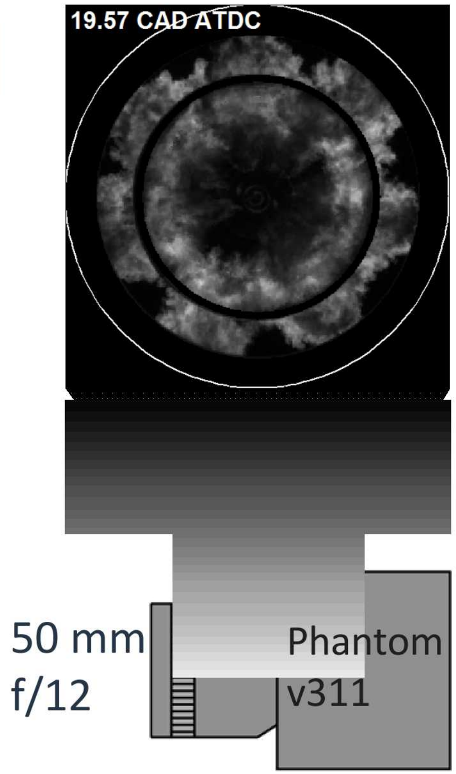
- Combustion is faster because rates of mixing-controlled heat release are higher with the stepped-lip piston

  → Turbulent flow and mixing must play a key role

  - Focus for optical experiments and simulations:
    spray-wall interactions and turbulent flow evolution

Experimental study of turbulent flow evolution





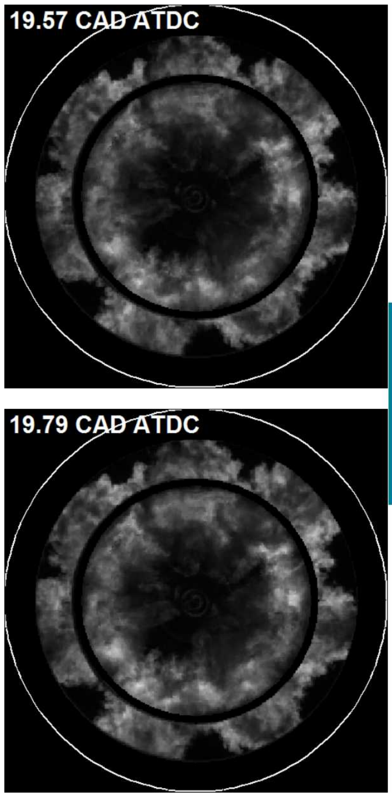
Frame rate: 40 kHz
Exposure: 2.5 µs

- Objective: characterize turbulent flow topology during the mixing-controlled portion of the cycle
- Combustion image velocimetry (CIV): detecting motion in high-speed natural luminosity images[1]
  - Raytracing-based image distortion correction
  - PIV-like cross correlation routine
- Line-of-sight integration makes interpretation challenging, but the goal is a qualitative description of turbulent flow evolution

[1]Dembinski, H. W. R. and Angstrom, H.-E., "Optical Study of Swirl during Combustion in a CI Engine with Different Injection Pressures and Swirl Ratios Compared with Calculations." SAE Technical Paper 2012-01-0682, 2012, DOI: 10.4271/2012-01-0682.

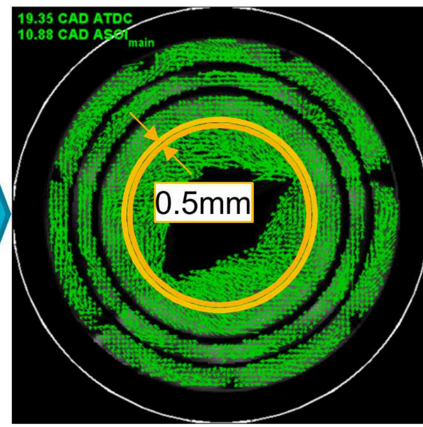
Characterization of radial flow using CIV

Natural luminosity image pairs



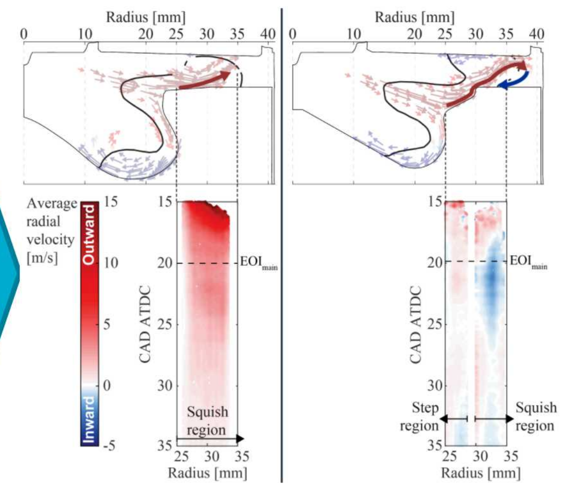
Distortion correction, cross correlation

Crank angle resolved flow fields



Azimuthal averaging over annular regions

Spatio-temporally resolved radial velocity

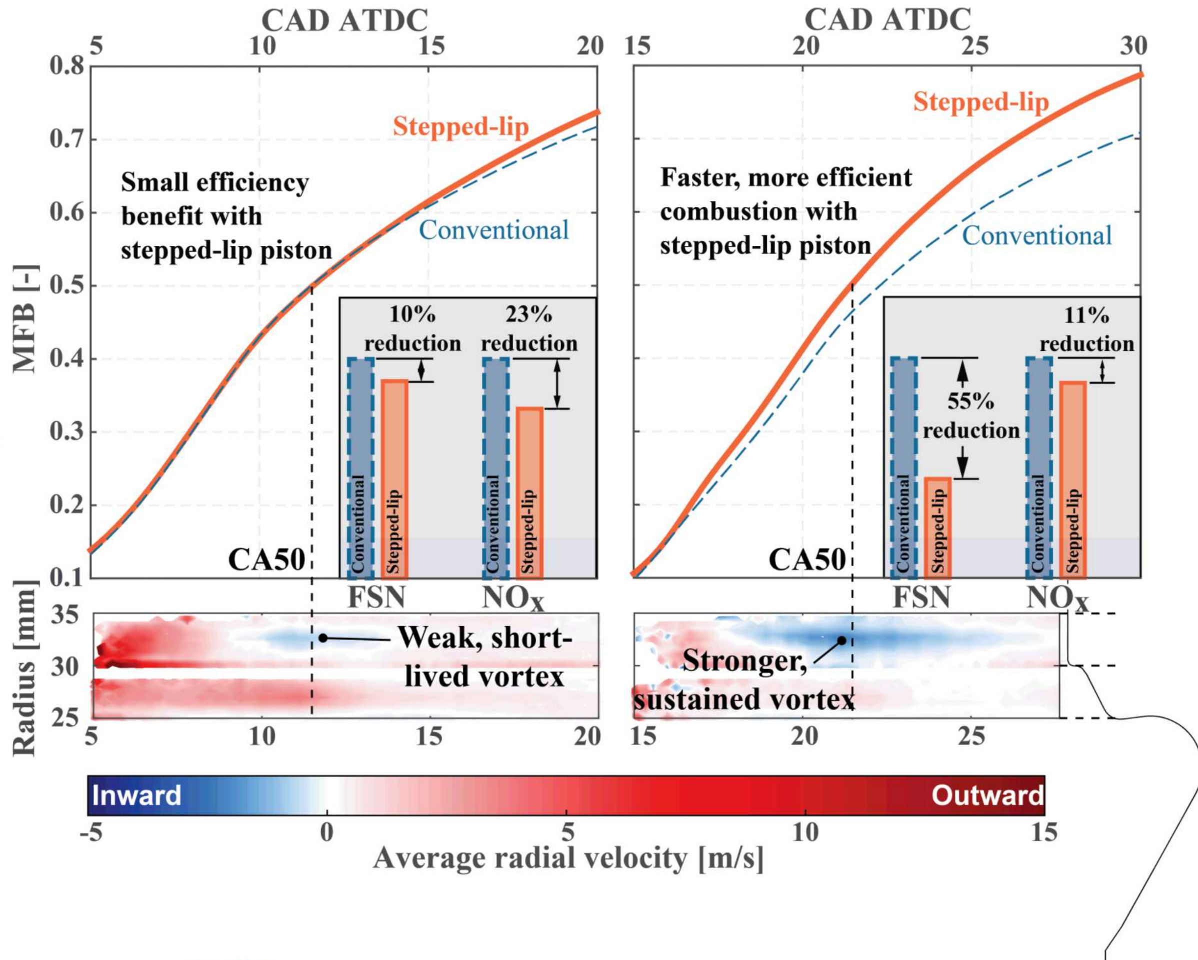


CIV provides evidence of recirculating flow structures in the stepped-lip combustion chamber

- Efficiency and soot emissions advantages of the stepped-lip piston correlate with the intensity/longevity of the squish-region vortex
- This finding supports, but does not prove, a theory proposed in the literature that enhanced air utilization in the squish region enhances mixing with the stepped-lip piston[1]
- We need a deeper understanding of spray-wall interactions and vortex formation

Near-TDC main injection timing

Intermediate main injection timing



[1]Kurtz, E. M. and Styron, J., "An Assessment of Two Piston Bowl Concepts in a Medium-Duty Diesel Engine," *SAE Int. J. Engines* 5(2):344-352, 2012, DOI: 10.4271/2012-01-0423

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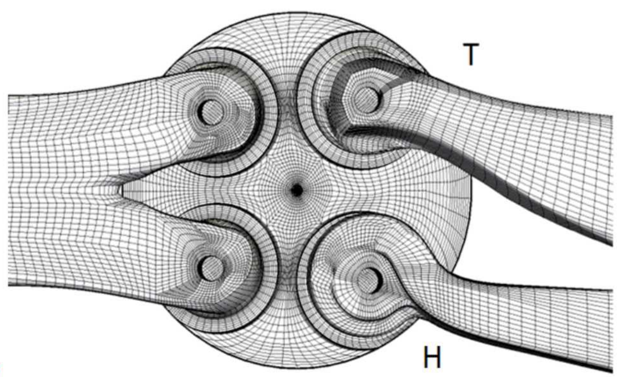
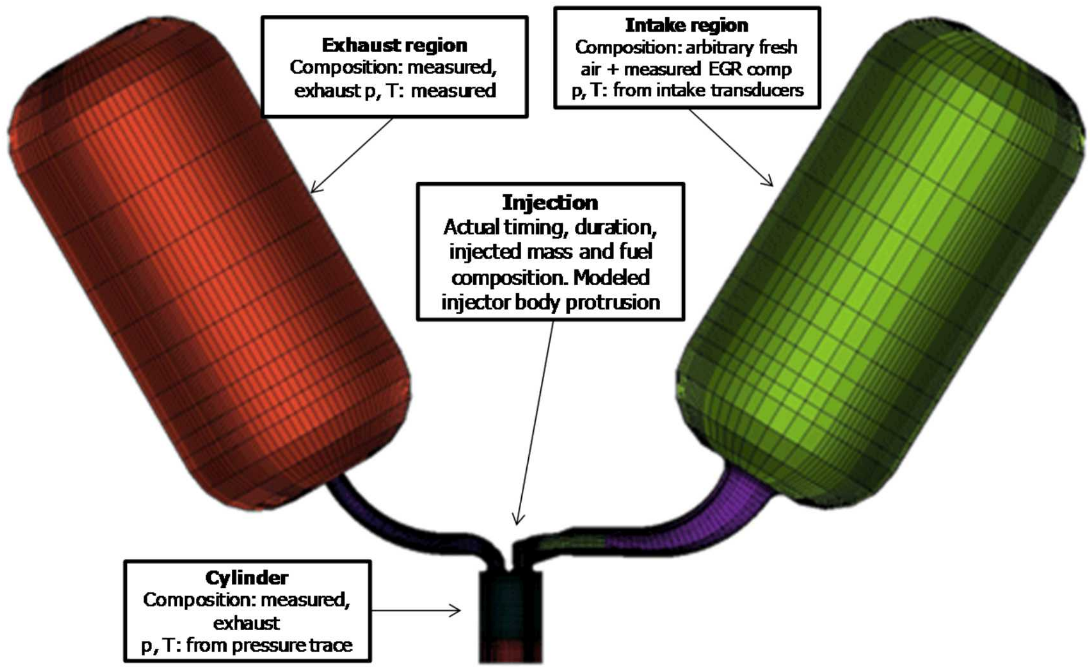
CFD simulation setup

Engine configuration	
Compression ratio	16.1 : 1
Squish height at TDC [mm]	1.36
Operating conditions	
Engine speed [rev/min]	1500
Intake pressure [bar]	1.5
Intake temperature [K]	353
Injection pressure [bar]	800
Swirl Ratio (Ricardo) [-]	2.2
Intake charge [mol fr.]	0% O_2
FRESCO solver setup	
mesh type:	Body-fitted, unstructured hexahedral mesh
time accuracy:	hybrid 1st-order implicit (diffusion, momentum) / explicit (advection)
spatial accuracy:	2nd-order (diffusion) upwind (advection)

- Reynolds-averaged Navier-Stokes (RANS) equations are solved using the FRESCO solver (Federico Perini, Wisconsin Engine Research Consultants)
- Simulations are performed for the full engine, including intake and exhaust systems



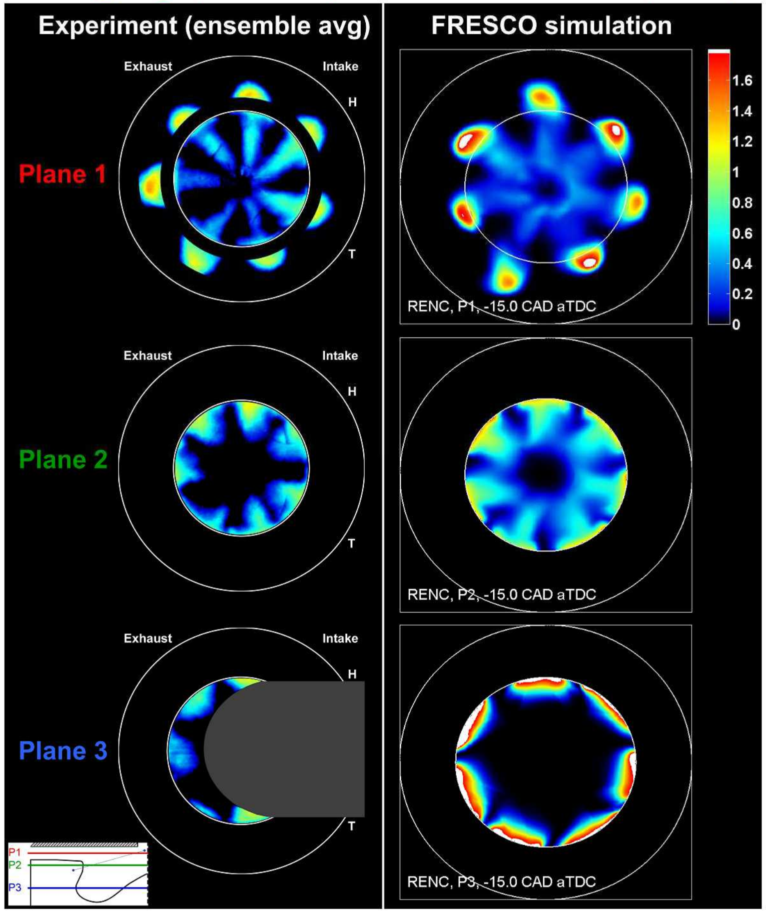


Evaluation of CFD simulation capabilities

- ECN Spray A data are used to calibrate spray models and evaluate turbulence models
- Liquid scattering imaging and quantitative fuel tracer fluorescence images are used to evaluate CFD predictions of spray penetration and deflection by swirl
- Prediction of liquid behavior is very reasonable (not shown)
  - Initial penetration is very well captured
  - Liquid fuel vaporizes before impinging on bowl
- Spray penetration and deflection predictions are very good (see images), but certainly not perfect
  - Current predictions are the most accurate we've seen and clearly better than previous efforts using sector meshes

Fuel tracer PLIF imaging (Sandia)

RANS simulations (UW)



CFD predictions of turbulent flow evolution

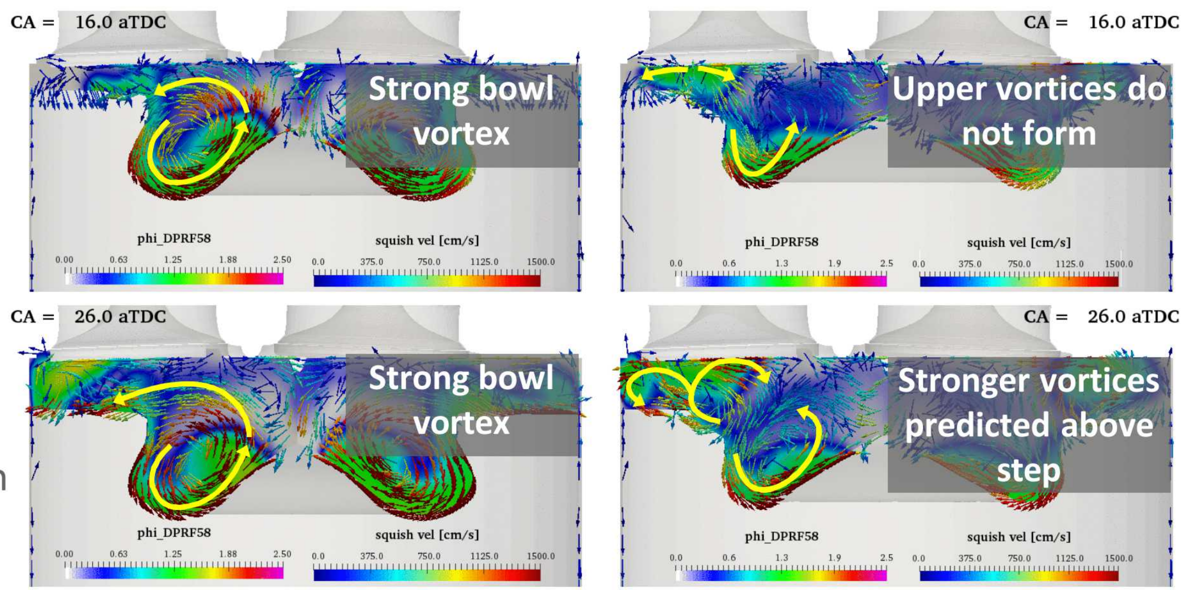
- Flow in the conventional combustion chamber is dominated by the toroidal vortex in the bowl and is relatively insensitive to injection timing

- Flow evolution in the stepped-lip combustion chamber depends on injection timing
  - Intermediate timing: counter rotating vortices predicted above the step and in the squish region

Conventional bowl | **Stepped-lip bowl**

Near-TDC main injection

Intermediate main injection



Vortex formation – key to enhancing turbulent mixing?

- The formation of energetic, long-lived vortices corresponds with faster combustion and therefore greater efficiency
- The lack of vortex formation at the near-TDC injection timing is believed to be responsible for the diminished efficiency benefit
- **Hypothesis:** if vortex formation mechanisms can be enhanced at the near-TDC injection timing, then improvements in efficiency and pollutant emissions can be realized
- Focus first on understanding vortex formation for the intermediate injection timing

Examining the RANS equations in the radial direction

Radial acceleration is normalized by the local velocity magnitude:

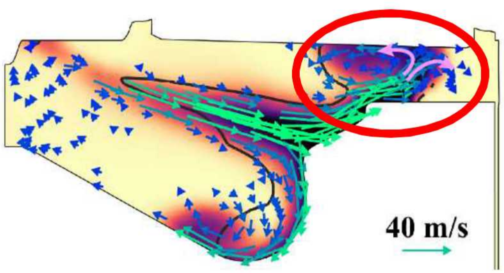
Convection terms

$$\frac{1}{|\vec{u}|}\frac{\partial u_r}{\partial t} = \frac{-1}{\rho|\vec{u}|}\frac{\partial p}{\partial r} + \frac{1}{|\vec{u}|}\frac{u_\theta^2}{r} - \frac{u_r}{|\vec{u}|}\frac{\partial u_r}{\partial r} - \frac{u_\theta}{r|\vec{u}|}\frac{\partial u_r}{\partial \theta} - \frac{u_z}{|\vec{u}|}\frac{\partial u_r}{\partial z} + \frac{1}{\rho|\vec{u}|}\frac{\partial \tau_{ij}}{\partial r} + \frac{\mu}{|\vec{u}|}(\dots)$$

Pressure gradient | Centrifugal | Radial | Tangential | Vertical | Turbulence | Viscosity

These terms determine the evolution of radial flow

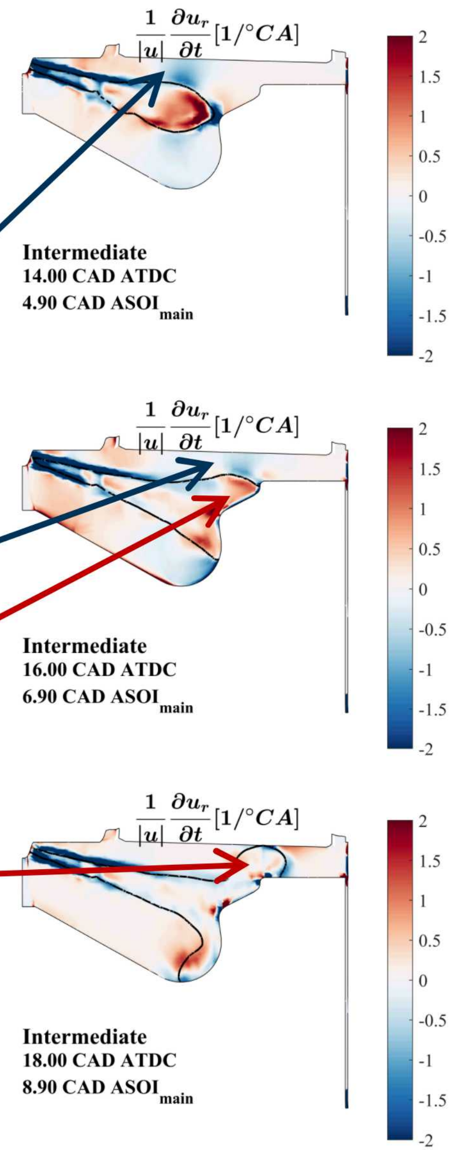
- Examination focused on a vertical cutting plane containing a spray axis
- What drives radial flow evolution above the step when vortices are predicted to form?



Velocity-normalized radial acceleration

$$\frac{1}{|\vec{u}|}\frac{\partial u_r}{\partial t} = \frac{-1}{\rho|\vec{u}|}\frac{\partial p}{\partial r} + \frac{1}{|\vec{u}|}\frac{u_\theta^2}{r} - \frac{u_r}{|\vec{u}|}\frac{\partial u_r}{\partial r} - \frac{u_\theta}{r|\vec{u}|}\frac{\partial u_r}{\partial \theta} - \frac{u_z}{|\vec{u}|}\frac{\partial u_r}{\partial z} + \frac{1}{\rho|\vec{u}|}\frac{\partial \tau_{ij}}{\partial r} + \frac{\mu}{|\vec{u}|}(\dots)$$

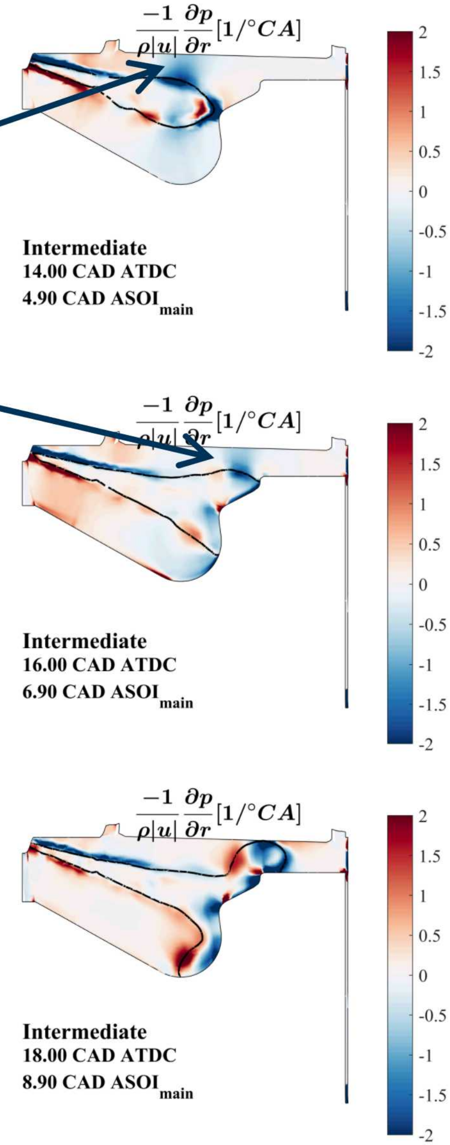
- Velocity-normalized acceleration: units of inverse time
  - Normalized by engine speed; shown with units of 1/°CA
- False-color scale
  - Red: outward acceleration
  - Blue: inward acceleration
- As spray penetrates outward and downward, inward acceleration regions form
- Outward acceleration is predicted in the interior of the spray
- **What is responsible for the inward and outward acceleration?**



Contribution of radial pressure gradient

$$\frac{1}{|\vec{u}|}\frac{\partial u_r}{\partial t} = \frac{-1}{\rho|\vec{u}|}\frac{\partial p}{\partial r} + \frac{1}{|\vec{u}|}\frac{u_\theta^2}{r} - \frac{u_r}{|\vec{u}|}\frac{\partial u_r}{\partial r} - \frac{u_\theta}{r|\vec{u}|}\frac{\partial u_r}{\partial \theta} - \frac{u_z}{|\vec{u}|}\frac{\partial u_r}{\partial z} + \frac{1}{\rho|\vec{u}|}\frac{\partial \tau_{ij}}{\partial r} + \frac{\mu}{|\vec{u}|}(\dots)$$

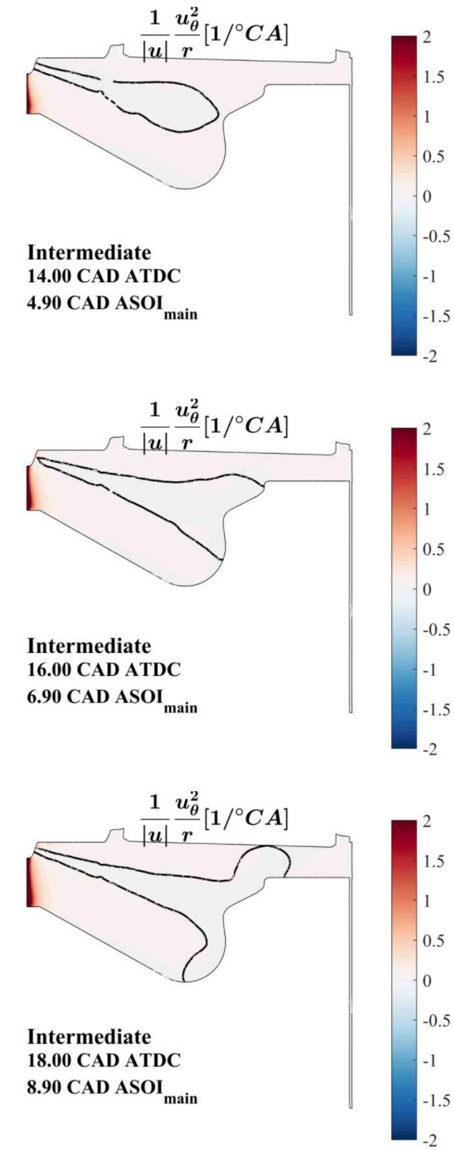
- An adverse radial pressure gradient above the spray is transported into the entrance of the squish region
- This adverse radial pressure gradient drives inward acceleration beneath the cylinder head



Contribution of centrifugal force

$$\frac{1}{|\vec{u}|}\frac{\partial u_r}{\partial t} = \frac{-1}{\rho|\vec{u}|}\frac{\partial p}{\partial r} + \frac{1}{|\vec{u}|}\frac{u_\theta^2}{r} - \frac{u_r}{|\vec{u}|}\frac{\partial u_r}{\partial r} - \frac{u_\theta}{r|\vec{u}|}\frac{\partial u_r}{\partial \theta} - \frac{u_z}{|\vec{u}|}\frac{\partial u_r}{\partial z} + \frac{1}{\rho|\vec{u}|}\frac{\partial \tau_{ij}}{\partial r} + \frac{\mu}{|\vec{u}|}(\dots)$$

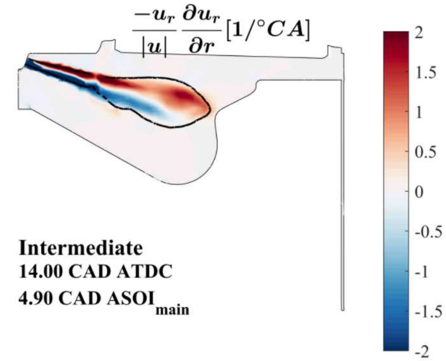
- Centrifugal forces do not play a role in the evolution of flow in this vertical plane

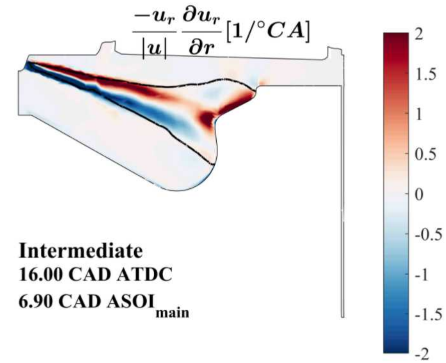


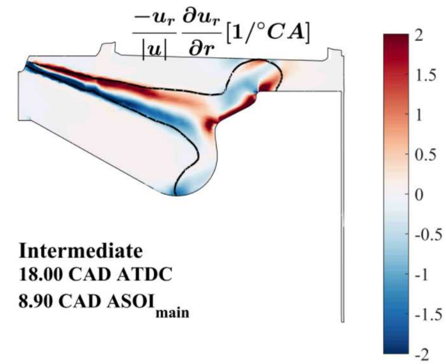
Contribution of radial convection

$$\frac{1}{|\vec{u}|}\frac{\partial u_r}{\partial t} = \frac{-1}{\rho|\vec{u}|}\frac{\partial p}{\partial r} + \frac{1}{|\vec{u}|}\frac{u_\theta^2}{r} - \frac{u_r}{|\vec{u}|}\frac{\partial u_r}{\partial r} - \frac{u_\theta}{r|\vec{u}|}\frac{\partial u_r}{\partial \theta} - \frac{u_z}{|\vec{u}|}\frac{\partial u_r}{\partial z} + \frac{1}{\rho|\vec{u}|}\frac{\partial \tau_{ij}}{\partial r} + \frac{\mu}{|\vec{u}|}(\ldots)$$

- Radial convection does not create significant inward acceleration near the cylinder head
- Nor does it create outward acceleration in the center of the spray



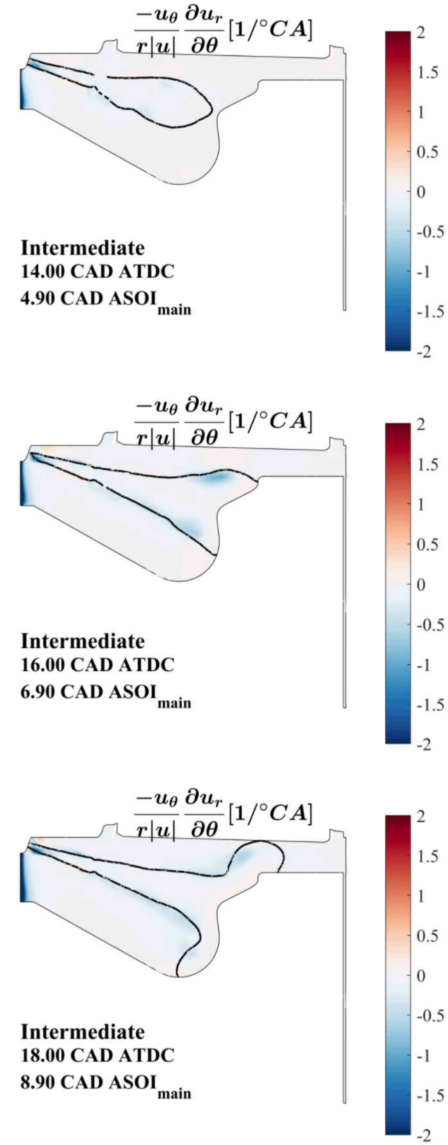




Contribution of tangential convection

$$\frac{1}{|\vec{u}|}\frac{\partial u_r}{\partial t} = \frac{-1}{\rho|\vec{u}|}\frac{\partial p}{\partial r} + \frac{1}{|\vec{u}|}\frac{u_\theta^2}{r} - \frac{u_r}{|\vec{u}|}\frac{\partial u_r}{\partial r} - \frac{u_\theta}{r|\vec{u}|}\frac{\partial u_r}{\partial \theta} - \frac{u_z}{|\vec{u}|}\frac{\partial u_r}{\partial z} + \frac{1}{\rho|\vec{u}|}\frac{\partial \tau_{ij}}{\partial r} + \frac{\mu}{|\vec{u}|}(\dots)$$

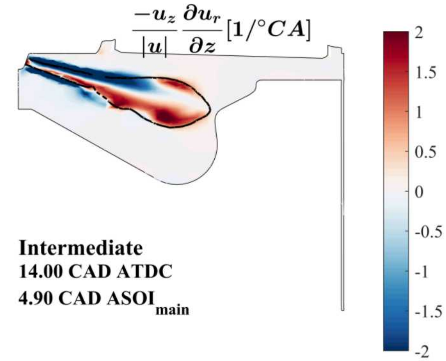
- Tangential convection of radial momentum does not control vertical-plane flow evolution

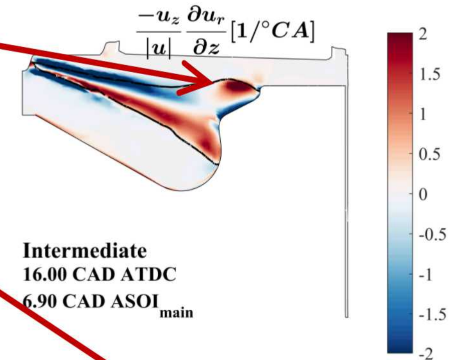


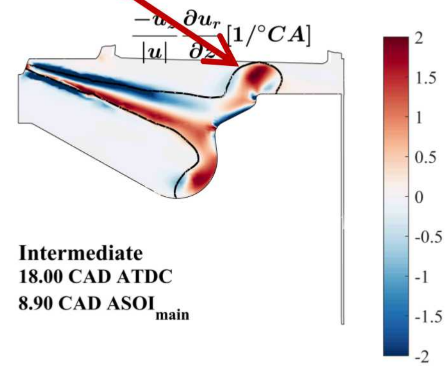
Contribution of vertical convection

$$\frac{1}{|\vec{u}|}\frac{\partial u_r}{\partial t} = \frac{-1}{\rho|\vec{u}|}\frac{\partial p}{\partial r} + \frac{1}{|\vec{u}|}\frac{u_\theta^2}{r} - \frac{u_r}{|\vec{u}|}\frac{\partial u_r}{\partial r} - \frac{u_\theta}{r|\vec{u}|}\frac{\partial u_r}{\partial \theta} - \frac{u_z}{|\vec{u}|}\frac{\partial u_r}{\partial z} + \frac{1}{\rho|\vec{u}|}\frac{\partial \tau_{ij}}{\partial r} + \frac{\mu}{|\vec{u}|}(\ldots)$$

- Vertical convection of radial momentum is responsible for outward acceleration in the center of the spray as it penetrates into the squish region



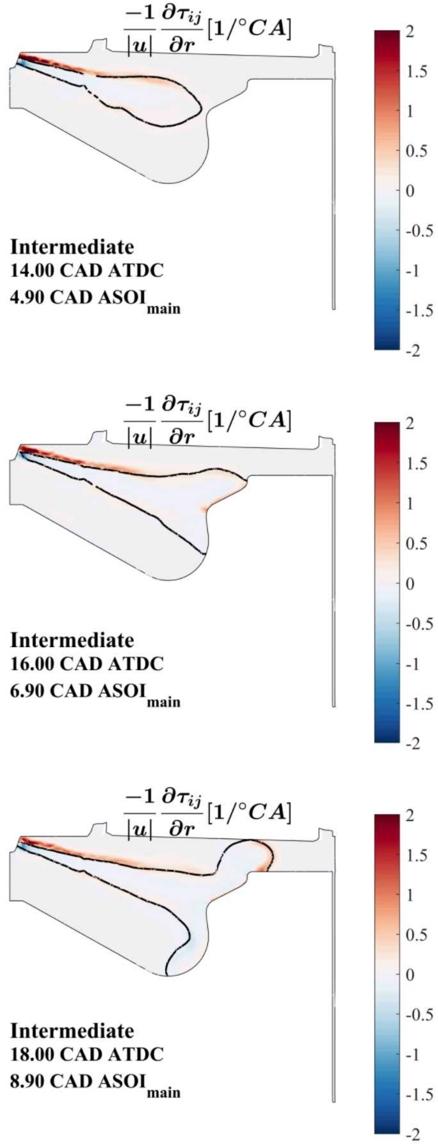




Contribution of turbulence

$$\frac{1}{|\vec{u}|}\frac{\partial u_r}{\partial t} = \frac{-1}{\rho|\vec{u}|}\frac{\partial p}{\partial r} + \frac{1}{|\vec{u}|}\frac{u_\theta^2}{r} - \frac{u_r}{|\vec{u}|}\frac{\partial u_r}{\partial r} - \frac{u_\theta}{r|\vec{u}|}\frac{\partial u_r}{\partial \theta} - \frac{u_z}{|\vec{u}|}\frac{\partial u_r}{\partial z} - \frac{1}{\rho|\vec{u}|}\frac{\partial \tau_{ij}}{\partial r} + \frac{\mu}{|\vec{u}|}(\dots)$$

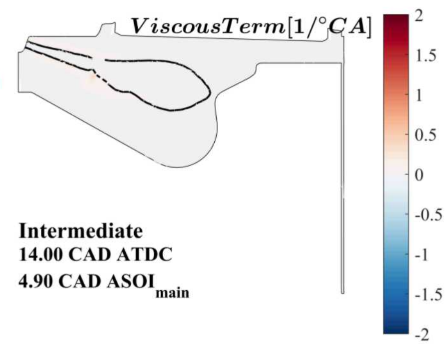
- Turbulence affects radial acceleration in the spray periphery, but plays a second-order role in the evolution of flow in the vertical plane near the step

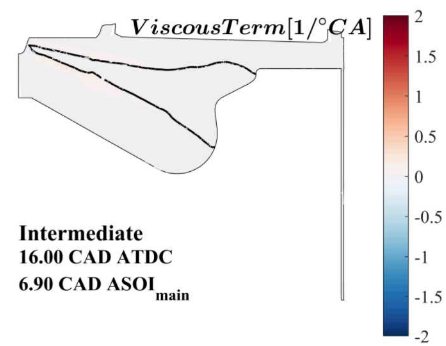


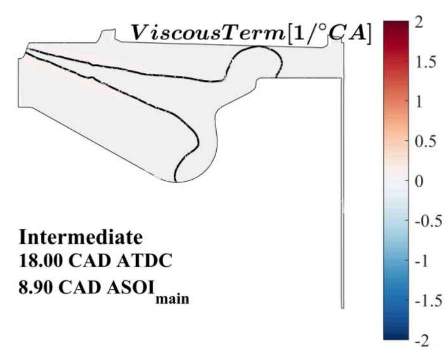
Contribution of viscosity

$$\frac{1}{|\vec{u}|}\frac{\partial u_r}{\partial t} = \frac{-1}{\rho|\vec{u}|}\frac{\partial p}{\partial r} + \frac{1}{|\vec{u}|}\frac{u_\theta^2}{r} - \frac{u_r}{|\vec{u}|}\frac{\partial u_r}{\partial r} - \frac{u_\theta}{r|\vec{u}|}\frac{\partial u_r}{\partial \theta} - \frac{u_z}{|\vec{u}|}\frac{\partial u_r}{\partial z} + \frac{1}{\rho|\vec{u}|}\frac{\partial \tau_{ij}}{\partial r} + \frac{\mu}{|\vec{u}|}(\dots)$$

- Viscous forces are insignificant compared to forces due to convection and pressure



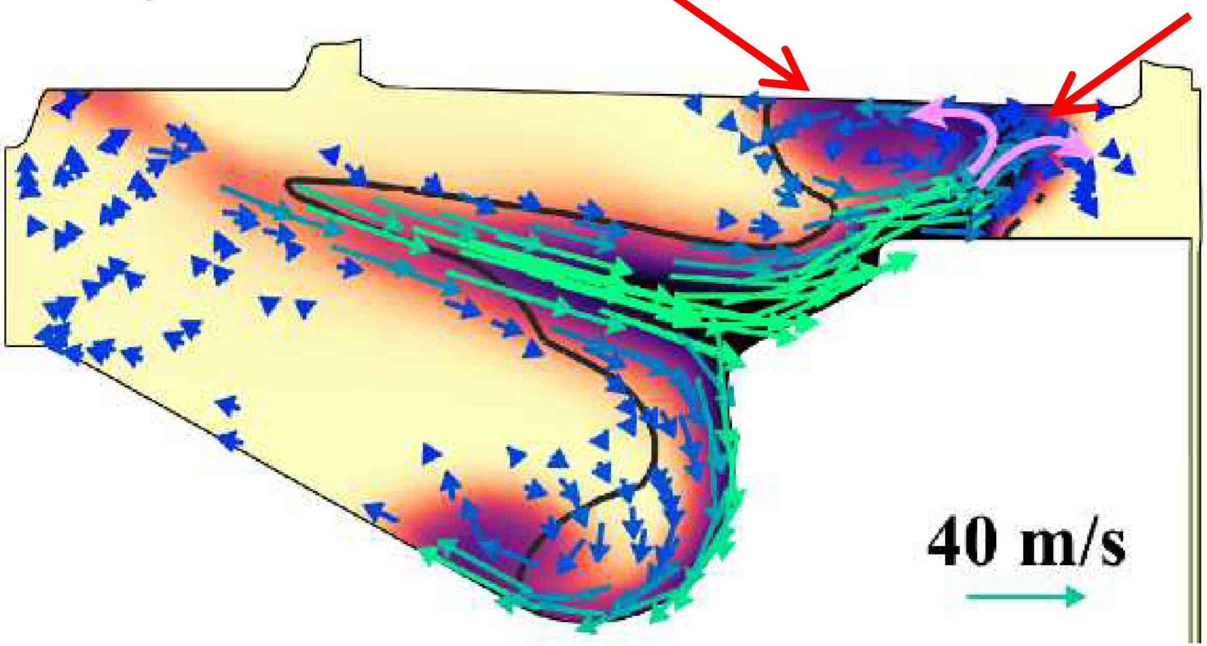




Recap: factors driving radial flow evolution

Adverse radial pressure gradient drives inward flow

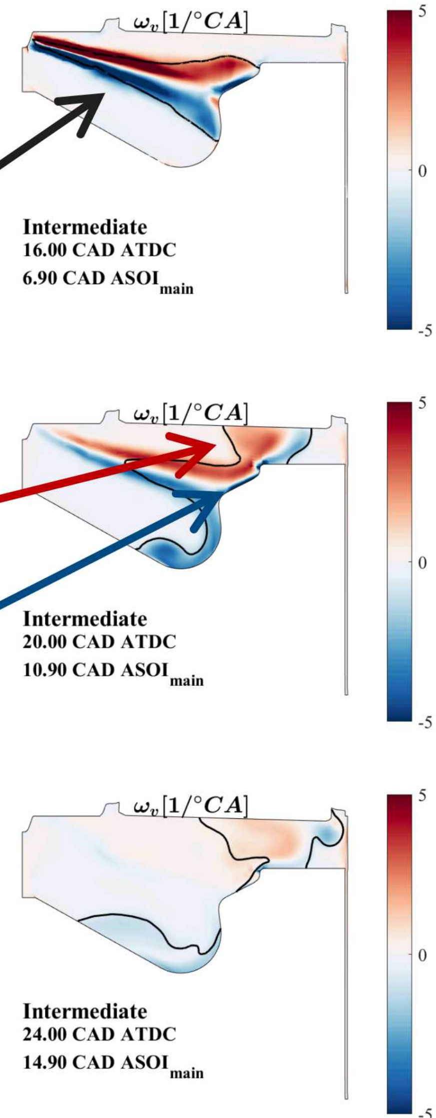
Convection of outward spray momentum drives outward flow



How is rotation established?

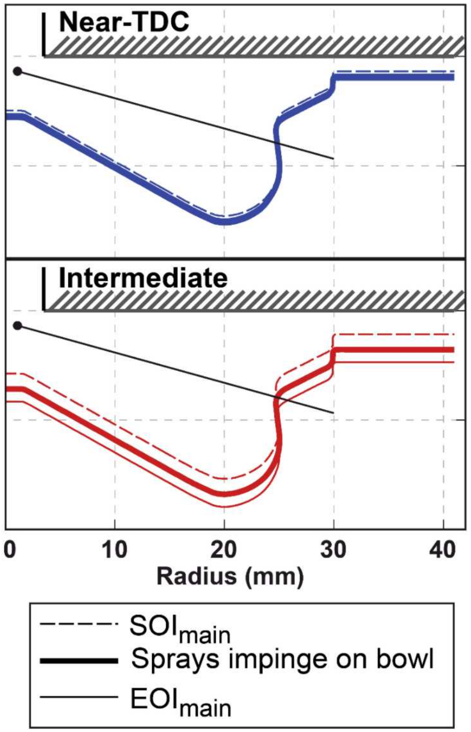
Evolution of vorticity

- Component of vorticity vector normal to vertical cutting plane visualized
  - Red: counterclockwise
  - Blue: clockwise
- Vorticity is introduced with the fuel injection and the strong velocity gradients it creates
- Counterclockwise rotation persists in the upper portion of the spray
- The viscous shear layer at the piston surface is a source of new clockwise vorticity
  - This vorticity is transported up and out into the squish region and promotes vortex formation



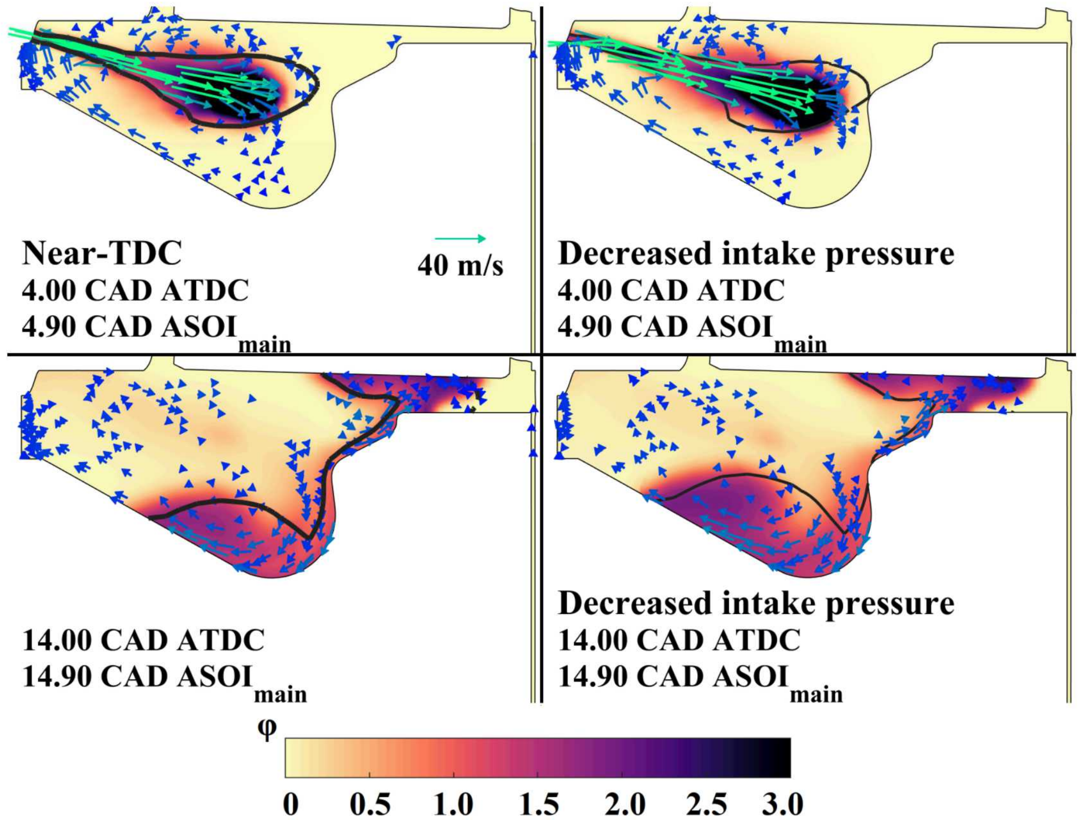
What changes as injection timing is advanced?

- Charge density
  - Higher air entrainment rates and lower spray penetration velocity
- Spray targeting
  - Impingement onto vertical surfaces vs. redirection upward into squish region
  - Splitting of fuel mass/momentum flow
- Space between cylinder head and piston surface
  - Constraint on flow structure may prevent vortex formation at near-TDC injection timings?



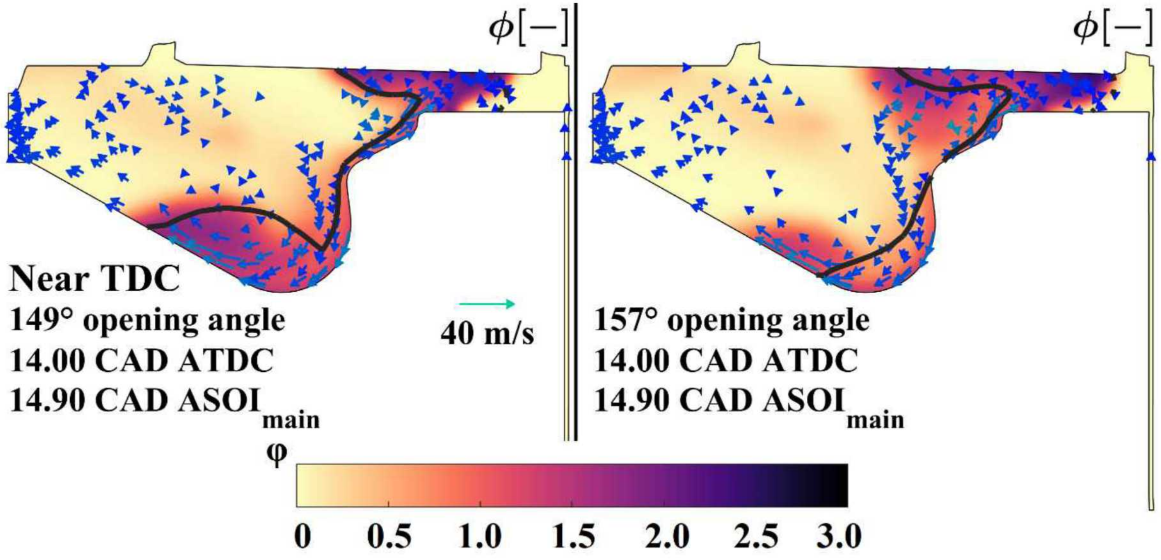
Charge density effects

- Reduce intake pressure to decrease near-TDC charge density
  - Is vortex formation enhanced?
  - With decreased charge density, penetration is faster but long-lived vortices do not form
  - Charge density is not the reason for decreased vortex action at the near-TDC timing



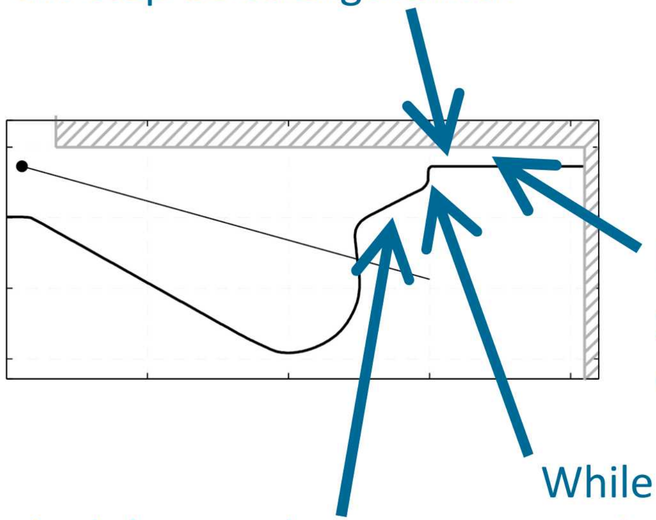
Spray targeting effects

- Spray targeting variation
  - Shifting injector upward creates interference with cylinder head – not possible
  - Increase injector opening angle to achieve the same spray targeting with the near-TDC main injection as for the intermediate main injection
- Changing spray targeting affects fuel mass/momentum splitting, but does not enhance vortex formation



Testing the hypothesis of squish region space

Can adverse radial pressure gradients above the step be strengthened?



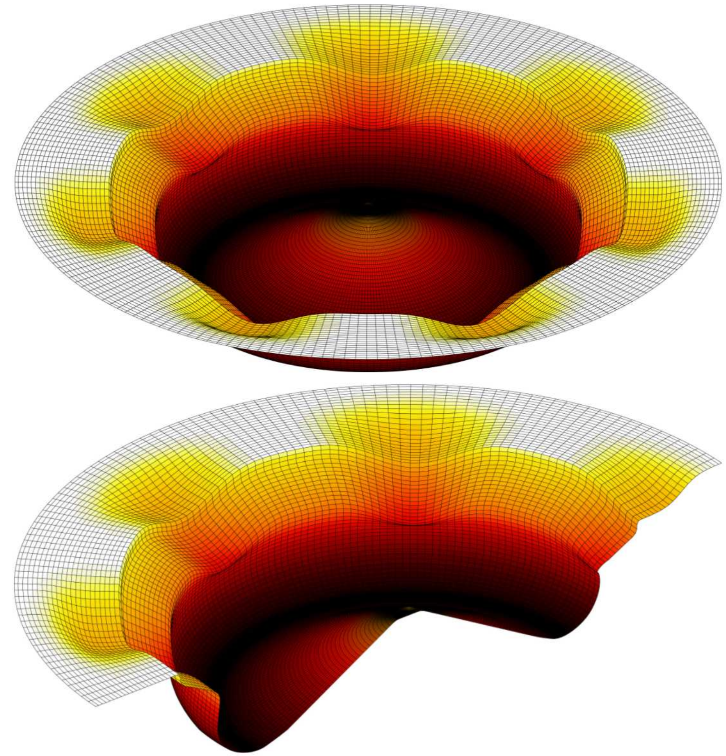
How can this space be expanded…

While preserving this vertical surface?

And the angular relationships of the step?

Dimpled stepped-lip (DSL) piston

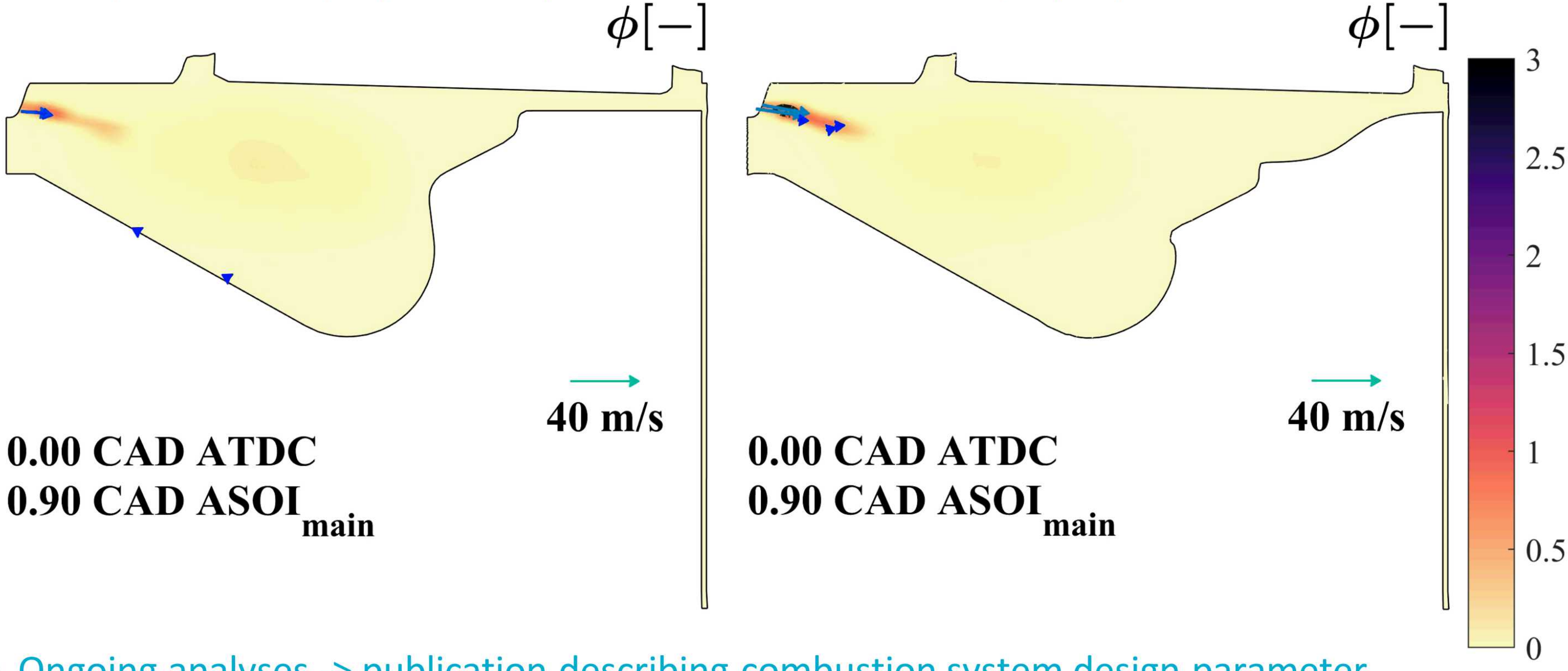
- Shift the step profile downward for each spray



Preliminary results with the dimpled stepped-lip piston demonstrate increased vortex formation

Stepped-lip: little vortex formation results from separation of spray from step

Dimpled stepped-lip: significant vortex formation as spray separates from step



- Ongoing analyses -> publication describing combustion system design parameter effects on flow and vortex evolution in progress

Summary

- The efficiency and emissions behavior of mixing-controlled combustion systems may be further improved through enhancements in turbulent mixing
- Spray-wall interactions with complex geometrical boundaries play an important role in determining turbulent flow evolution
- Increasing space in the squish region may enhance vortex formation and promote faster turbulent mixing
- Rotationally symmetric piston designs may become more popular if their influence on turbulent combustion yields significant benefits

Outlook

- Can the methodology applied in this work actually lead to improved diesel combustion systems?
  - New medium-duty diesel research engine: opportunity to test DSL piston hypothesis

- This study focused on a single stepped-lip design with a single speed-load point
  - What parameters of stepped-lip combustion system design are most important to promote formation of beneficial flow structures?
  - How do different engine speeds and loads affect turbulent flow evolution?

Acknowledgments

- Engine experiments
  - Kan Zha (Sandia)
- Computational support, simulation post-processing toolbox
  - Federico Perini (Wisconsin Engine Research Consultants)
- Technical input and project guidance
  - Alok Warey, Dick Peterson (GM)
  - Eric Kurtz (Ford)
- Laboratory operations assistance
  - Tim Gilbertson (Sandia)
- Financial support: DOE Office of Vehicle Technologies
  - Gurpreet Singh
  - Mike Weismiller

Thank you for your attention

Questions?