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Piston Bowl Geometry Impacts on Late-Cycle Flow and Mixing in a Small-Bore Diesel Engine

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In small-bore, swirl-supported diesel engines, piston bowl geometry can enhance late-cycle heat release (CA50-CA90), which increases thermal efficiency. The purpose of this computational study is to understand how piston bowl geometry impacts late-cycle flow and mixing with a conventional, re-entrant piston and with a stepped-lip piston bowl. The FRESCO CFD solver is used to simulate a conventional, part-load operating point with a pilot-main injection strategy for three main injection timings: shortly before TDC (near-TDC), approximately 9 CAD ATDC (intermediate), and 18 CAD ATDC (late). Experimental results have shown that for the intermediate injection timing, the late-cycle heat release is significantly enhanced by the stepped-lip piston, but this benefit is much smaller at the near-TDC and late injection timings. CFD results show that for the intermediate injection timing, the fuel jets impinge on the step and slightly more than half of the fuel is redirected upward toward the head. The upper portion of the jets impinges on the cylinder head and spreads laterally (both tangentially and radially). This impingement is also associated with the creation of two recirculation zones above the piston step and above the squish region. This spreading of mixture and of turbulence is believed to play a role in enhancing late-cycle heat release rates. For near-TDC injection timings, limited spacing between the step and the cylinder head appears to hinder lateral spreading and the observed additional recirculation phenomena are much less substantial. For late injection timings, the sprays impinge on the piston tops and the piston bowls do not play a significant role.

The Sandia small-bore engine geometry (including both piston bowl geometries) is now available on the ECN website and optical data for evaluating simulations will be uploaded to the ECN website in the coming weeks.

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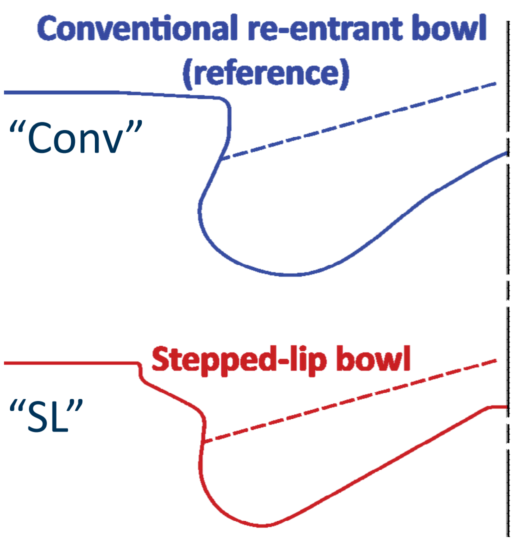
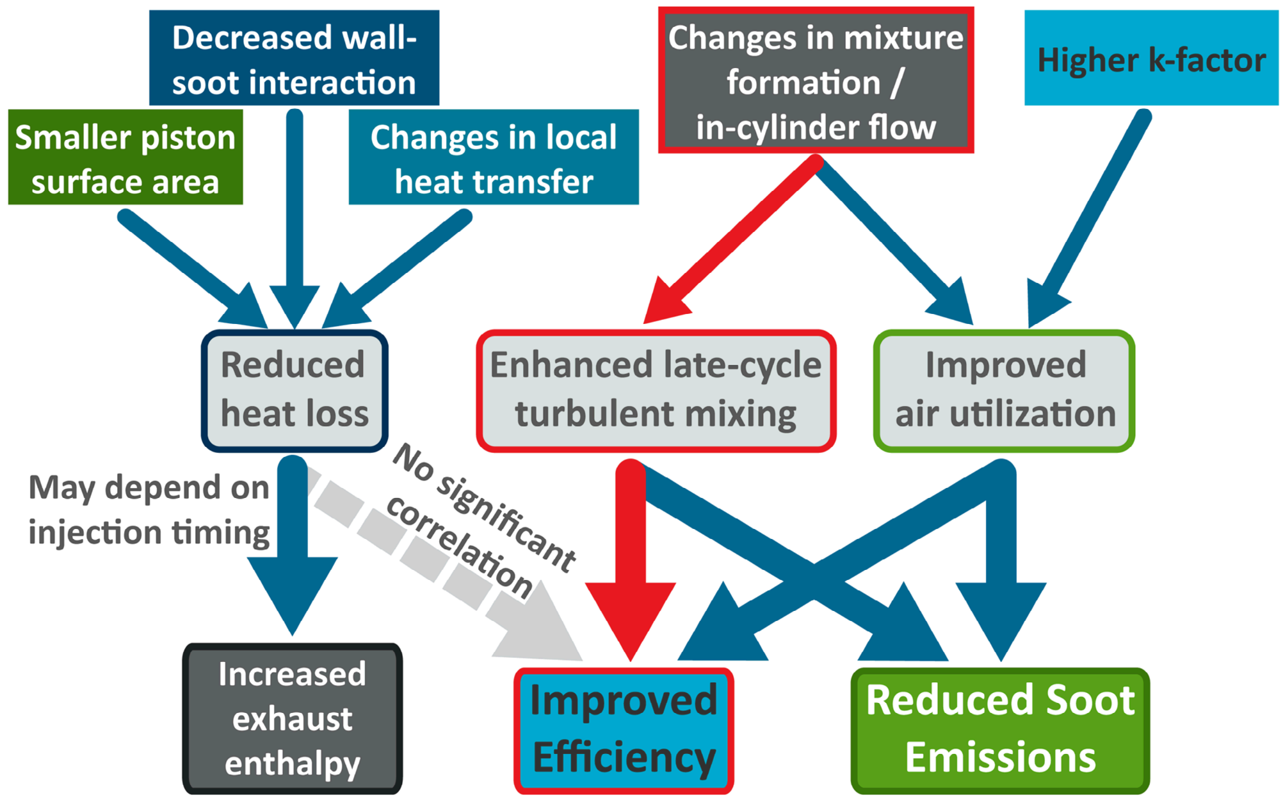
Outline

- Overview: piston bowl geometry project
- Computational study: bowl geometry impacts on late-cycle flow structure and turbulent mixing
  - Operating conditions, CFD setup (FRESCO)
  - Spray and turbulence model evaluation
  - Post processing methods
- Results
  - Bowl geometry impact on late-cycle flow structure, mixture distribution
  - Injection timing effects
- Summary: developing theory about late-cycle mixing mechanisms

Bowl geometry study overview

- Thermodynamic analysis: wall heat loss may depend on bowl geometry, but it does not have a significant impact on thermal efficiency (to be presented at SAE WCX 2018)
- Current focus: how does bowl geometry affect late-cycle flow structure and mixing?

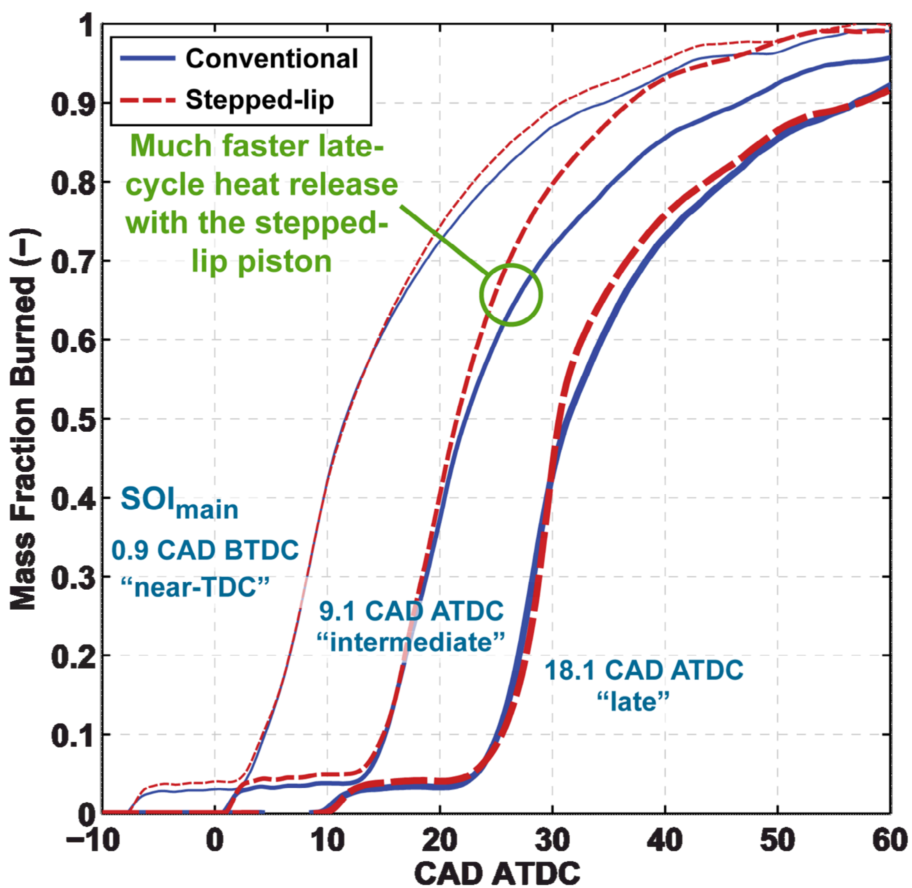




Operating conditions

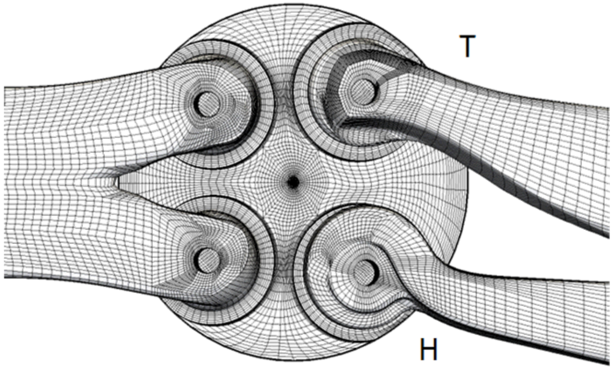
Part-load, conventional diesel combustion with a pilot-main injection strategy; three different injection timings

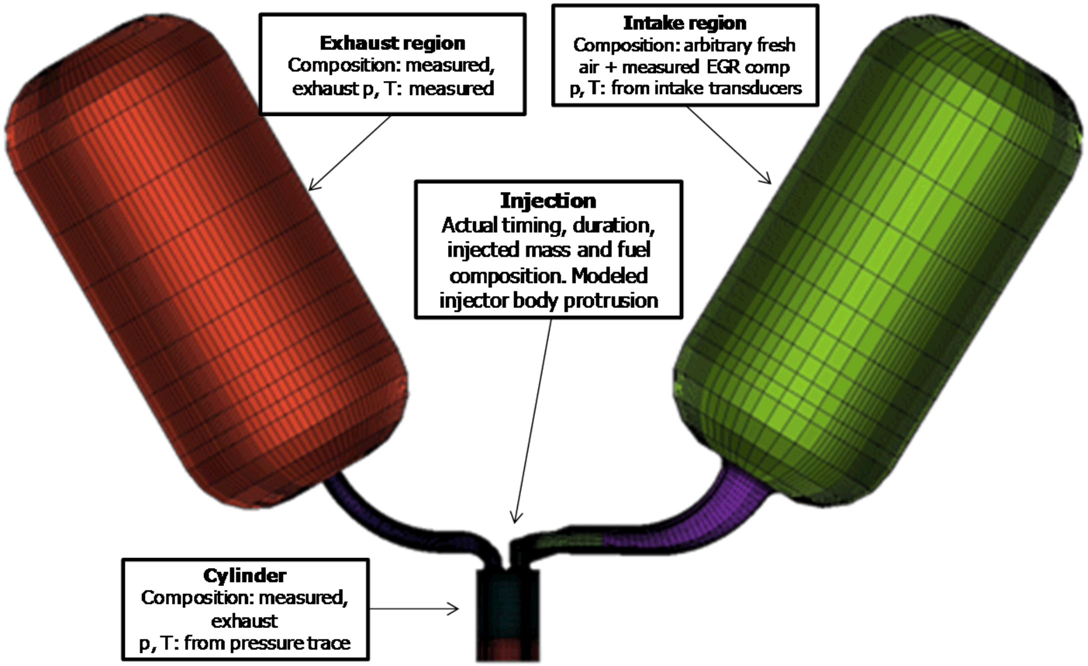
Engine speed	1500 rpm
$IMEP_g$	9.0 bar
Rail pressure	800 bar
m_{pilot}	1.5 mg/str
Pilot-main dwell	1200 µs
CA50	9.7-32 CAD ATDC
P_{intake}	150 kPa abs
T_{intake}	353 K
T_{TDC}	925 K (est.)
TDC density	21.8 kg/m³
EGR	7% (10.3% accounting for residual fraction)
$[O_2]_{intake}$	19.73%
Fuel	DPRF58 (CN 50.7) 58 vol% Heptamethylnonane 42 vol% n-Hexadecane



FRESCO 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)





Current spray and turbulence modeling approach in FRESCO

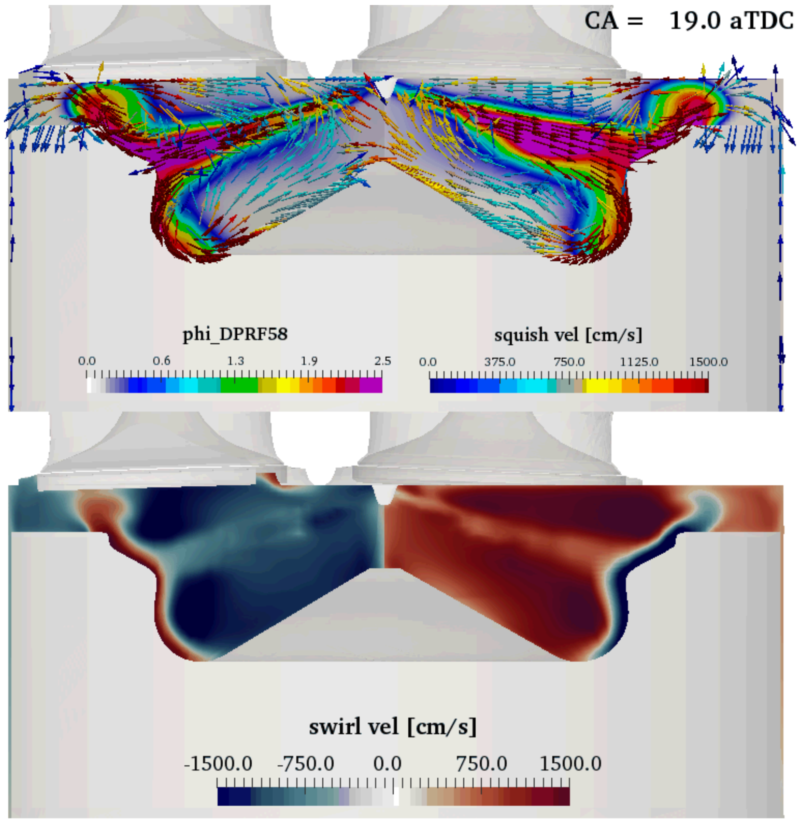
- State-of-the-art spray atomization, droplet collision, and sub-grid scale momentum coupling models have been implemented in FRESCO
- A multi-objective, genetic algorithm-based parameter optimization has been performed based on quantitative ECN data (Spray A)[1]
  - Numerous model constants with complex interactions have been optimized
  - Once optimized, the spray model parameters are not adjusted to provide a true test of the models' predictive capabilities
- A generalized RNG turbulence model has been evaluated for use in these simulations[2]
  - The GRNG model performs adequately for motored in-cylinder flow predictions and very well for jet flow predictions
  - ECN spray A flame structure is well predicted by the GRNG model

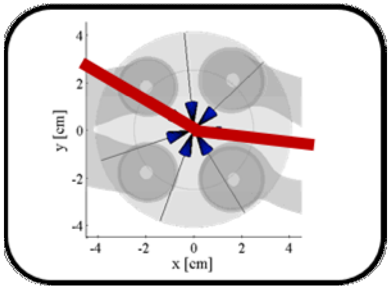
[1]Federico Perini, Rolf D. Reitz, Improved atomization, collision and sub-grid scale momentum coupling models for transient vaporizing engine sprays, International Journal of Multiphase Flow, Volume 79, March 2016, Pages 107-123, ISSN 0301-9322, DOI: /10.1016/j.ijmultiphaseflow.2015.10.009

[2]Perini, F., Zha, K., Busch, S. and Reitz, R., "Comparison of Linear, Non-Linear and Generalized RNG-Based k-epsilon Models for Turbulent Diesel Engine Flows," SAE Technical Paper 2017-01-0561, 2017, DOI: 10.4271/2017-01-0561

Post-processing of CFD results (1/4)

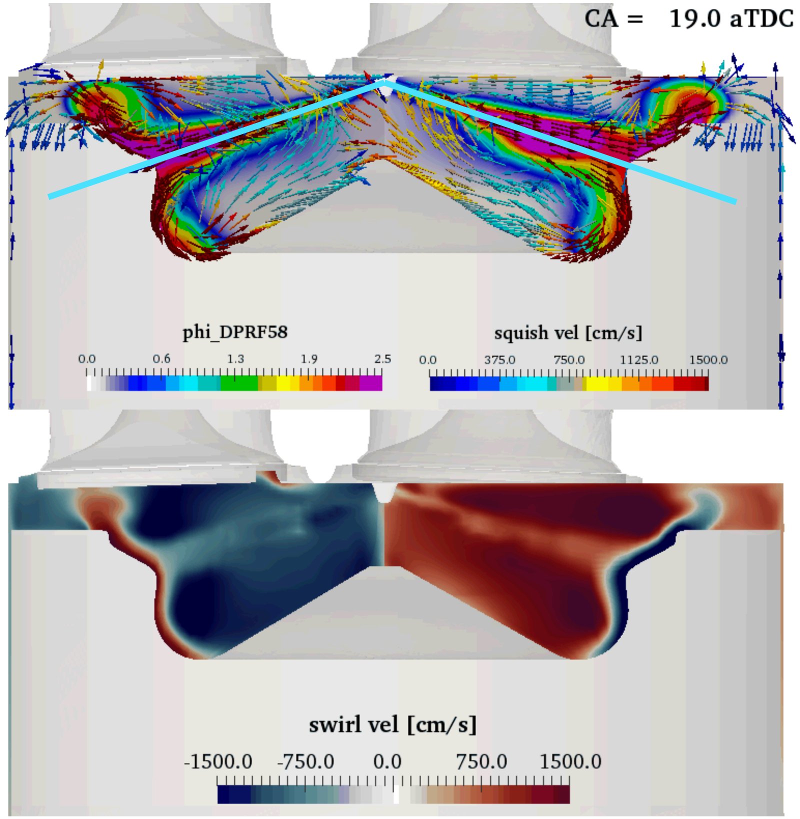
- Vertical half planes intersecting two jet axes are used to make a cross section
  - See cartoon at bottom right
- Top view: vertical plane flow and fuel concentration
  - Velocity projection onto vertical half-planes
  - Fuel-air mixture colored by ϕ
- Bottom view: tangential velocity
  - Depiction of swirling flow structures
- Still images and videos are shown





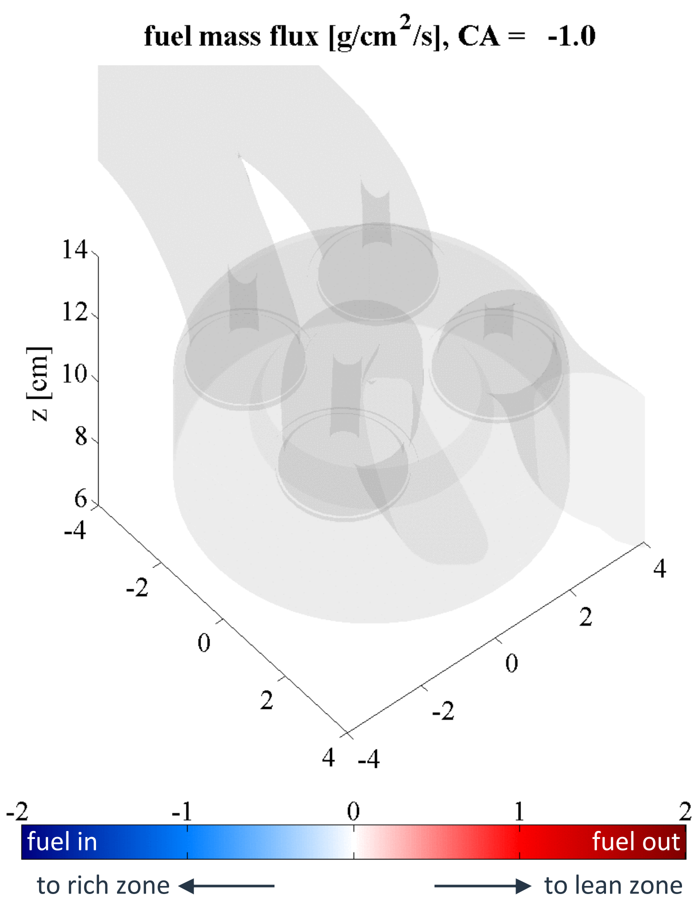
Post-processing of CFD results (2/4)

- Fuel splitting is quantified as follows:
  1. A cone containing the jet axes is defined (see image at right)
  2. A level-set field is defined such that the cone surface is identified by d=0
  3. d < 0: underneath the cone (bowl)
     d > 0: above the cone (squish)



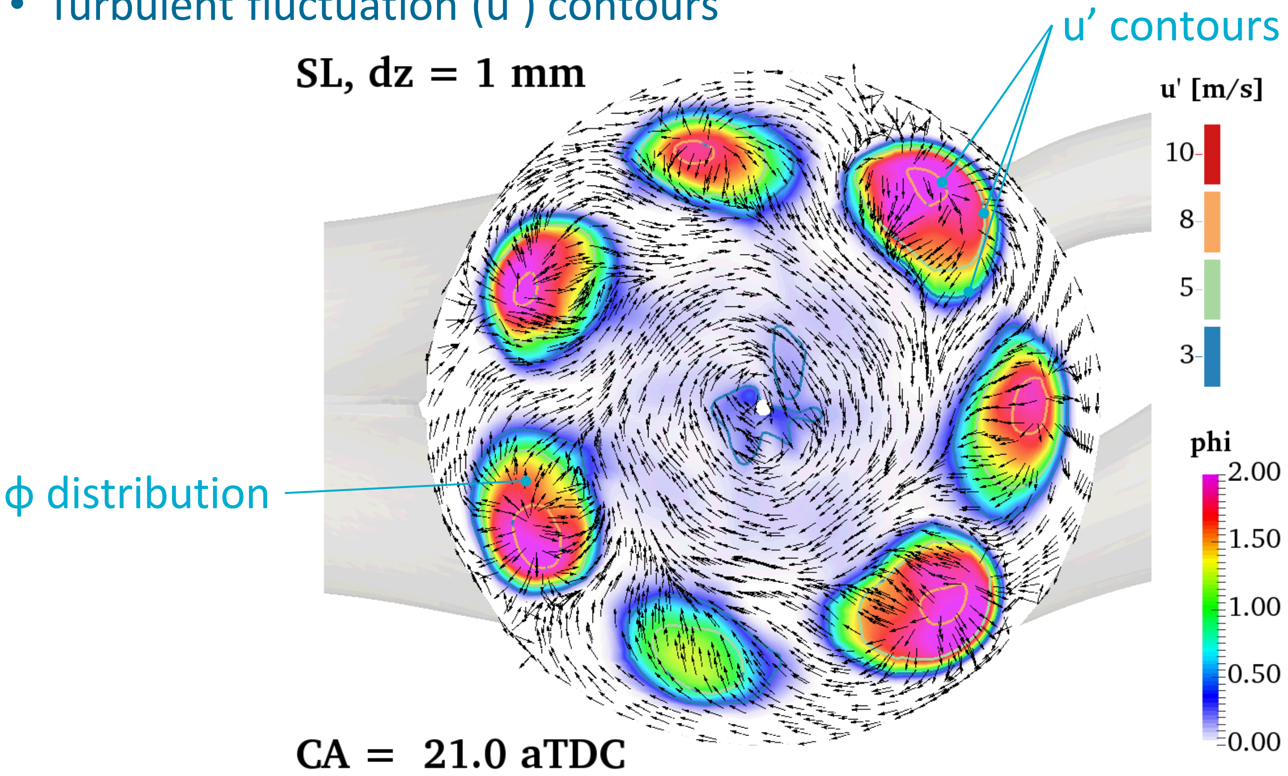
Post-processing of CFD results (3/4)

- To visualize and characterize mixing, the three-dimensional stoichiometric isosurface is computed
  - The mixtures inside this isosurface are richer than stoichiometric
- The isosurface shown at the right is colored by the local fuel mass flux
  - Fuel mass passing into the surface: blue
  - Fuel passing out of the surface into leaner mixtures: red
- The surface area/volume ratio of the stoichiometric isosurface is tracked
- Higher surface area/volume ratio:
  - Rich mixture cloud is less compact and spread over a larger portion of the cylinder
  - Potential for steeper concentration gradients
  - Higher potential for mixing



Post-processing of CFD results (4/4)

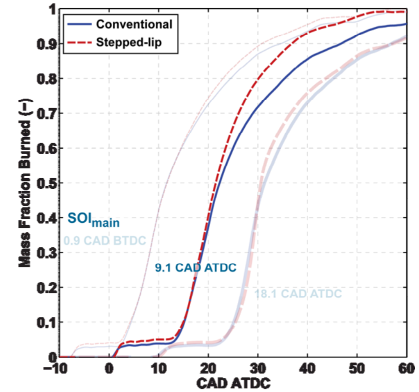
- Swirl-plane images
  - Cutting plane 1 mm below the head
  - Velocity field shown with black vectors
  - Fuel-air equivalence ratio (ϕ) shown with false-color
  - Turbulent fluctuation (u') contours

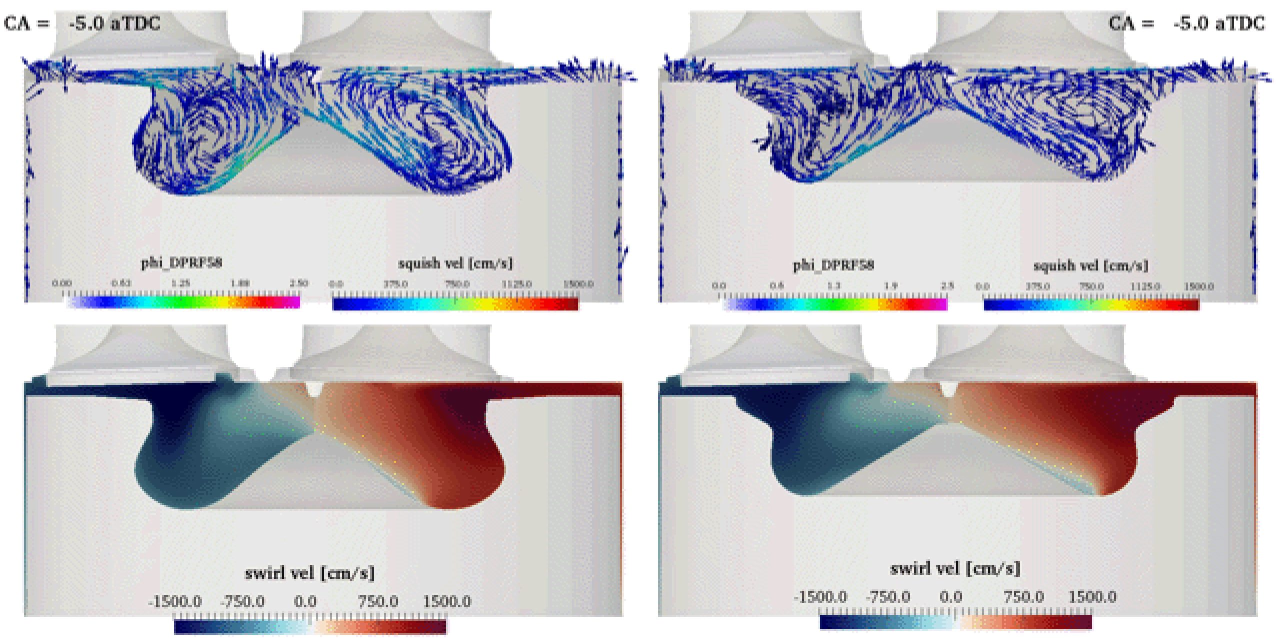


Intermediate injection timing: observations about jet-piston interactions and flow structure

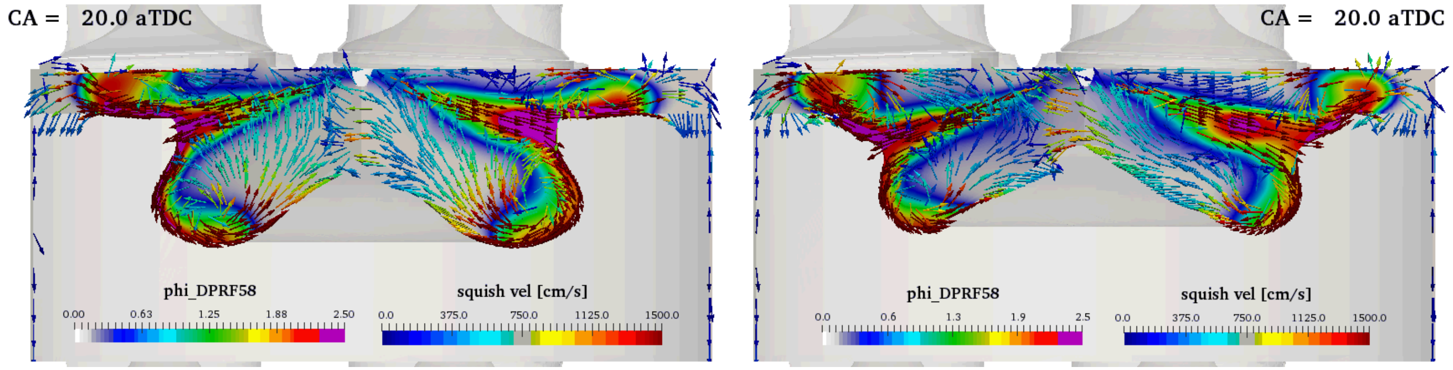
- Pilot injection
  - Does not interact directly with either bowl rim
- Main injection fuel splitting
  - Conv: some fuel redirected down into bowl, some sweeps across top of piston toward wall
  - SL: Upper portion of jet redirected upward at step; lower portion of jet redirected down into bowl
  - SL: upper portion impinges on cylinder head, spreads inward and outward
- Vortex dynamics
  - Conv: strong toroidal bowl vortex
  - SL: toroidal vortex forms in bowl; recirculation above step and above squish region

This is the injection timing at which late-cycle heat release is most effectively enhanced with the stepped-lip bowl

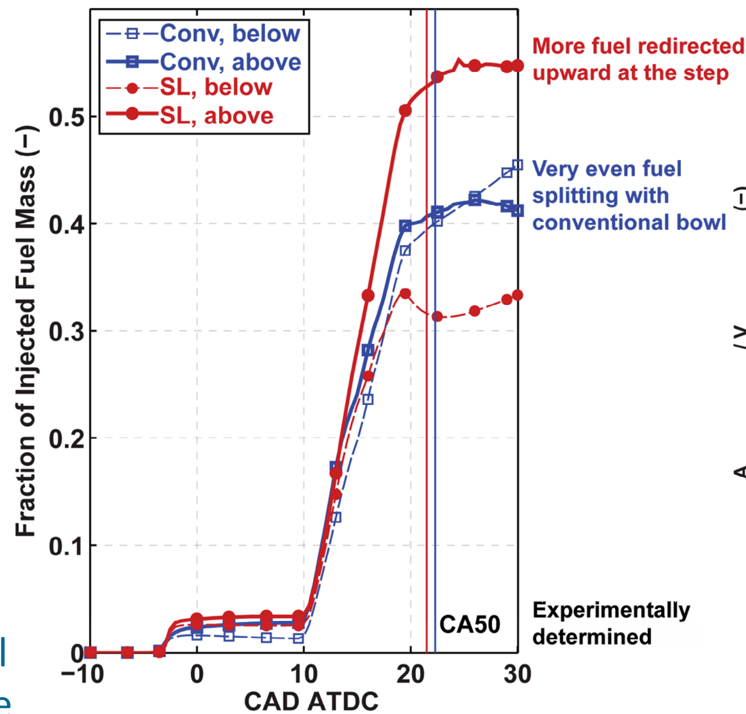


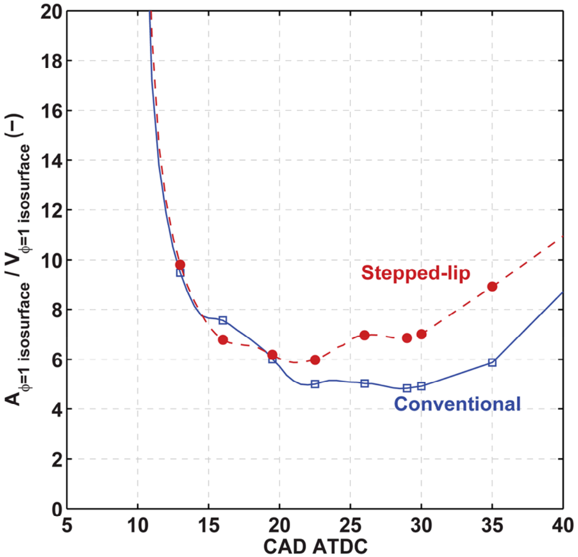


Intermediate injection timing: quantifying fuel splitting



- Conventional bowl
  - Nearly equal split above and below jet axes
- Stepped-lip bowl
  - Uneven split: ~60% of fuel vapor is directed upward after impinging on the conical surface of the step
- Surface area to volume ratio of stoichiometric isosurface
  - Higher for stepped-lip bowl after ~20 CAD ATDC despite uneven fuel splitting

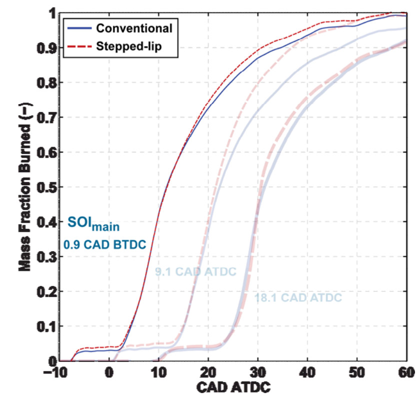


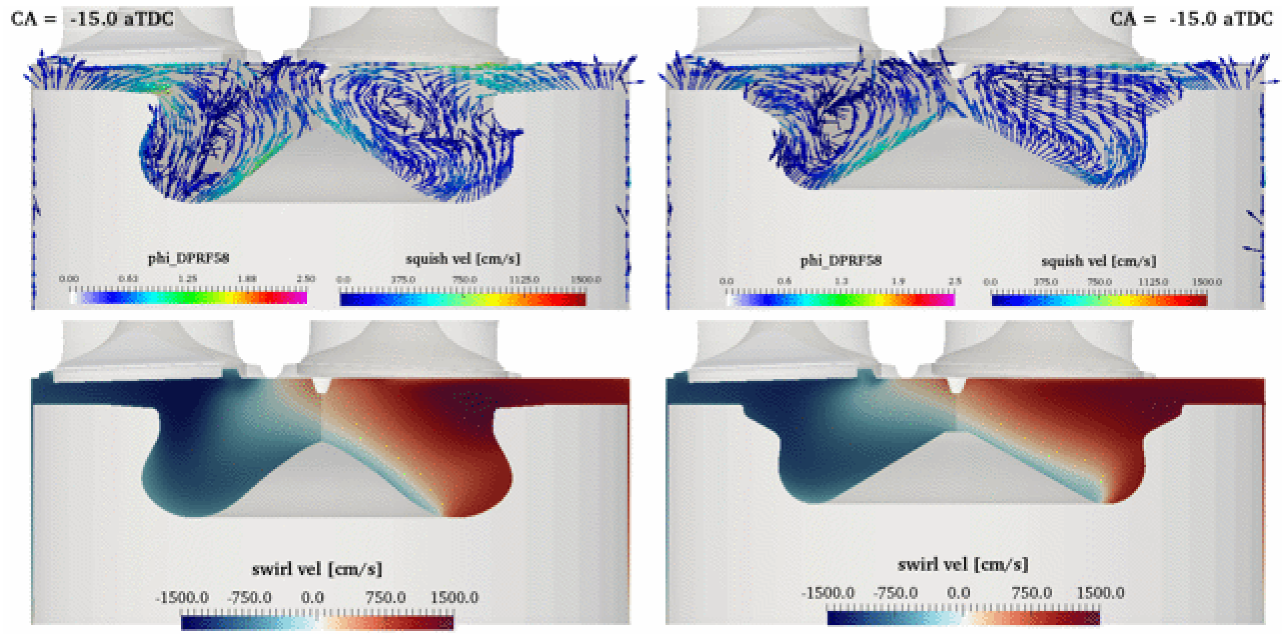


Near-TDC injection timing: observations about jet-piston interactions and flow structure

- Pilot injection
  - Does not interact directly with either bowl rim
- Main injection fuel splitting
  - Conv: most fuel redirected down into bowl
  - SL: Upper portion of jet redirected upward at step; lower portion of jet redirected down into bowl
  - SL: upper portion impinges on cylinder head, spreads inward and outward
- Vortex dynamics
  - Conv: strong toroidal bowl vortex, similar to intermediate injection timing
  - SL: toroidal vortex forms in bowl, but a well organized, long-lived vortex does not form above the step

Near-TDC injection timing: little difference between heat release profiles





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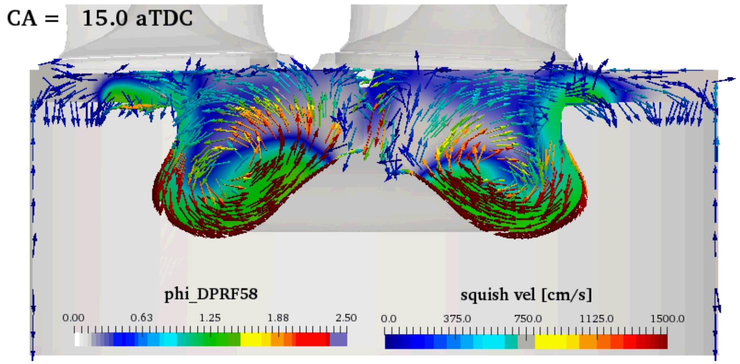
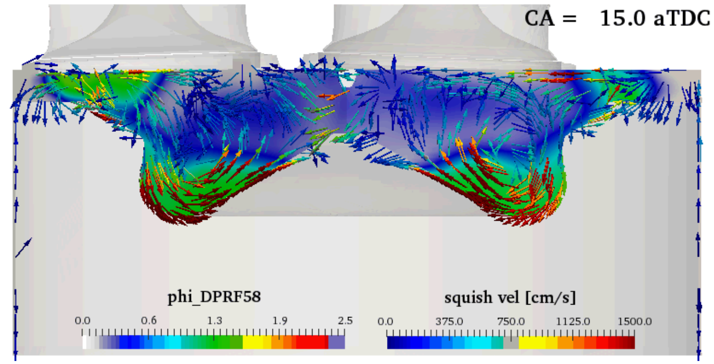
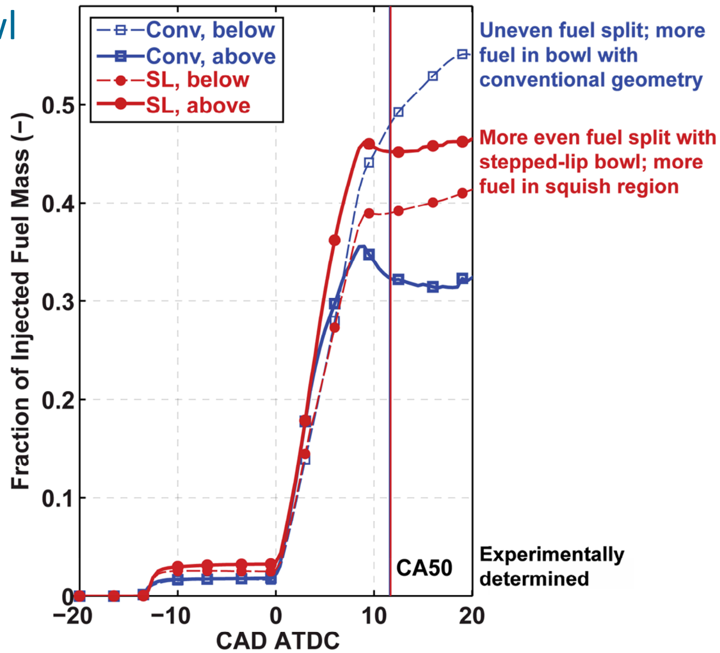
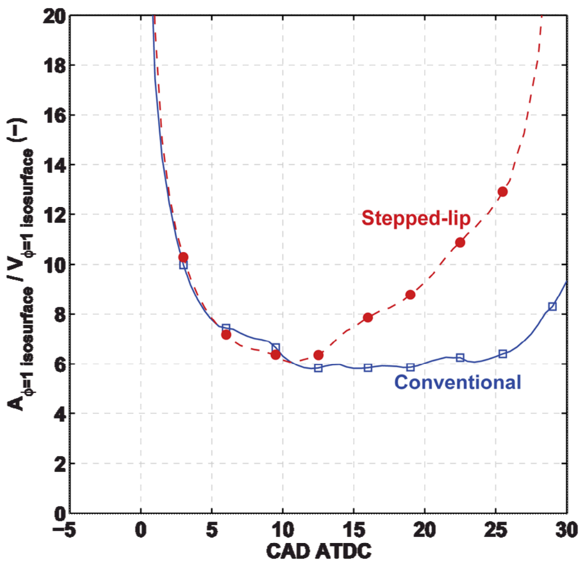
Near-TDC injection timing: quantifying fuel splitting





- Conventional bowl
  - Most fuel injected into bowl
- Stepped-lip bowl
  - Fuel splitting more even than for the conventional bowl, more even than at the intermediate injection timing
  - ~54% of fuel vapor is above jet axes
- Surface area to volume ratio of stoichiometric isosurface
  - Higher for stepped-lip bowl after ~10 CAD ATDC

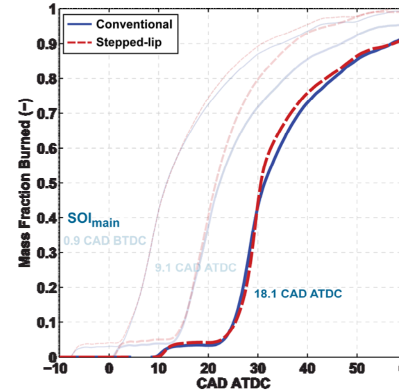


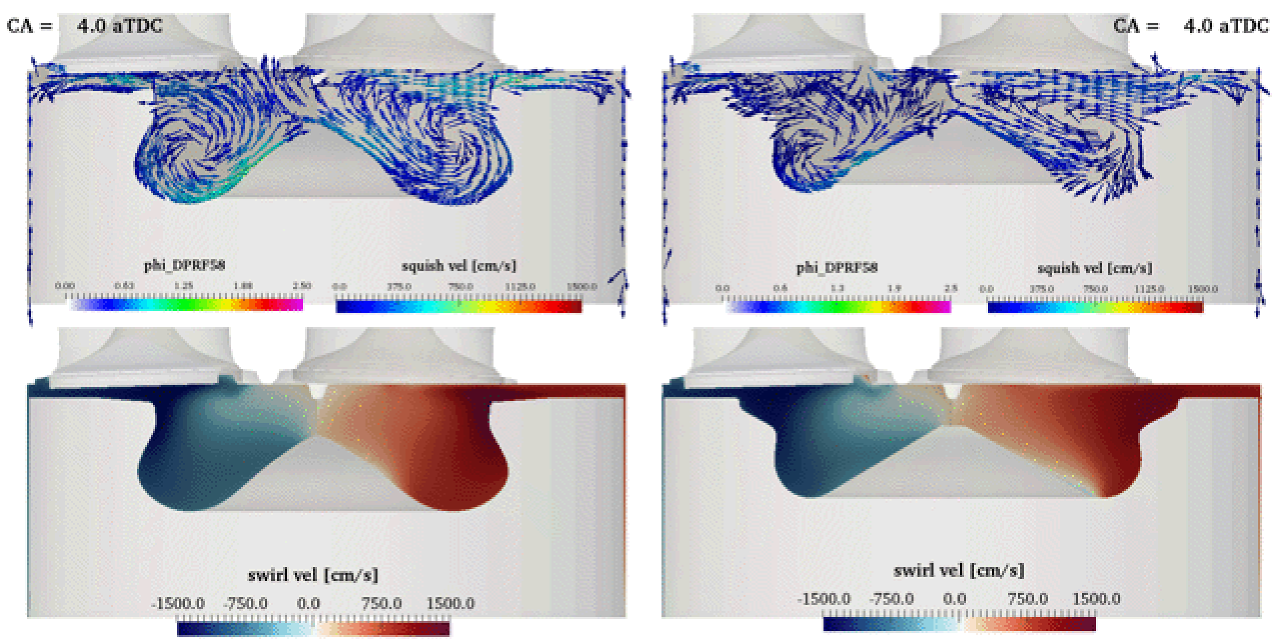


Late injection timing: observations about jet-piston interactions and flow structure

- Pilot injection
  - Does not interact directly with either bowl rim
- Main injection fuel splitting
  - Conv: most fuel is rapidly deflected by the top piston surface toward the liner
  - SL: Jets impinge on upper portion of step; most fuel is deflected upward and outward
  - SL: upper portion impinges on cylinder head, spreads inward and outward
- Vortex dynamics
  - Conv: weak toroidal bowl vortex, bore-sized toroidal vortex in the squish region
  - SL: weak bore-sized toroidal vortex in the squish region

Late injection timing: small differences between heat release profiles





Recap: overview of simulation results for injection timing sweep (conventional diesel combustion)

- CFD simulations with both bowl geometries predict significant impacts of varying injection timing on:
  - Fuel splitting / jet deflection
  - Late-cycle vortex dynamics
- For intermediate injection timings where late-cycle heat release rates are enhanced with the stepped-lip piston, CFD simulations predict the following:
  - Somewhat uneven fuel splitting: ~60% of fuel vapor is deflected upward at the step
  - Formation of multiple recirculation zones – well organized, long-lived and energetic; these are not observed for any other injection timing
- Focus on near-TDC and intermediate main injection timings
  - Do optical measurements support CFD predictions of late-cycle combustion structure?
  - Do simulations predict enhanced mixing with the stepped-lip bowl for the intermediate injection timing, but not the near-TDC injection timing? If so, what is the mechanism for enhanced mixing?

Do optical data support CFD predictions of late-cycle fluid dynamics (1/2)?

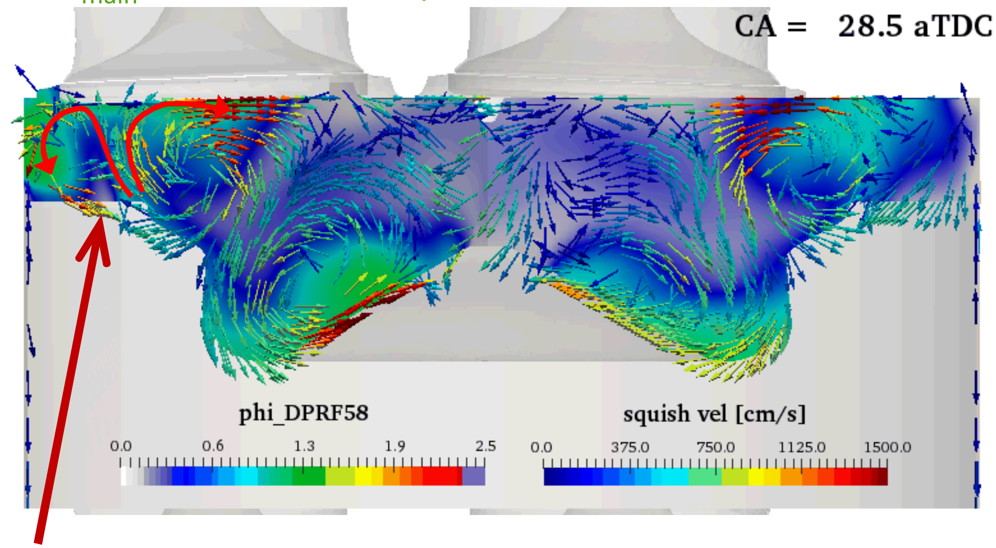
Fuel tracer PLIF data (LTC); image taken ~12 CAD after the start of injection. Note the apparent encroachment of fuel from the outer regions of the squish region.

SOI: 24 CAD BTDC; piston moves up

This phenomenon had yet to be predicted with simulations…

CFD results (CDC9); image taken ~ 20 CAD after SOI_{main}. A void in the mixture is sometimes visible above the step (see red arrow).

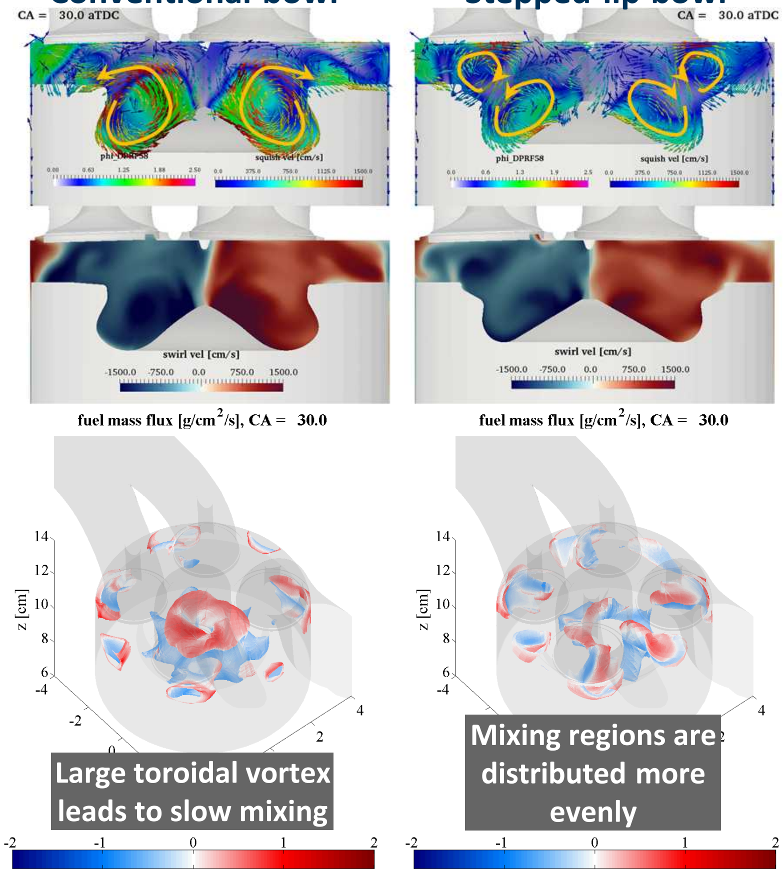
SOI_{main}: 9.5 CAD ATDC; piston moves down

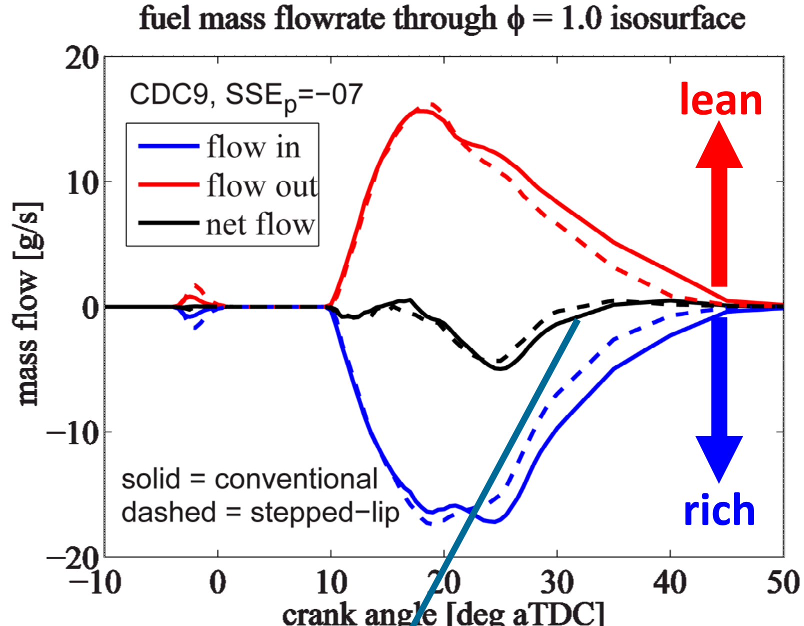


The upper portion of the jet impinges on the head and splits. The outward bound portion is redirected downward at the liner. The upper toroidal vortex transports the remaining mixture inward, away from the mixture in the outer squish region.

Do optical data support CFD predictions of late-cycle fluid dynamics (2/2)?

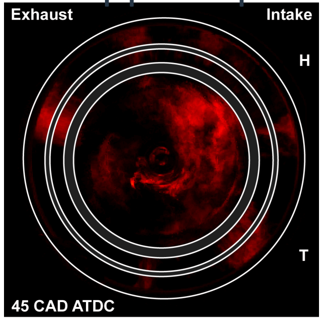
- Advanced post-processing techniques have been developed to provide insight into mixing processes predicted by FRESCO CFD simulations





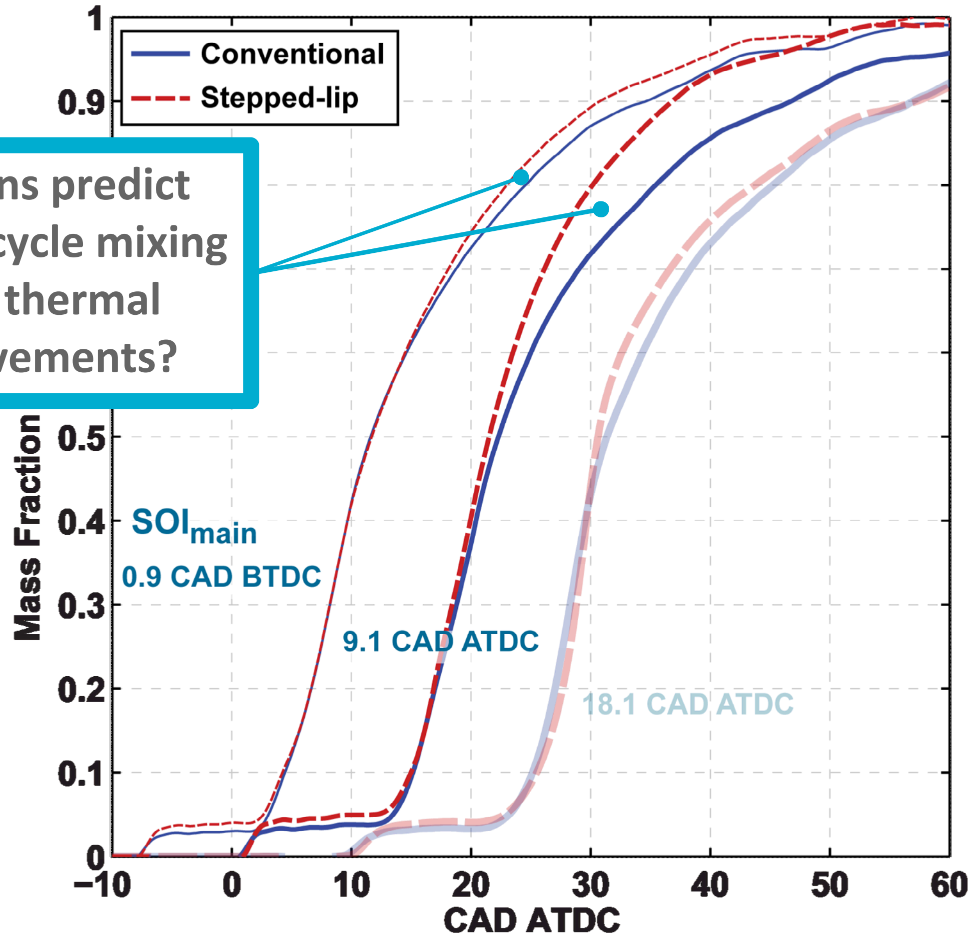
Richer conditions persist longer in the conventional bowl; natural luminosity images show a large amount of soot above the conventional bowl late in the cycle

Conventional Stepped-lip



Understanding the mechanism of enhanced late-cycle mixing with the stepped-lip bowl

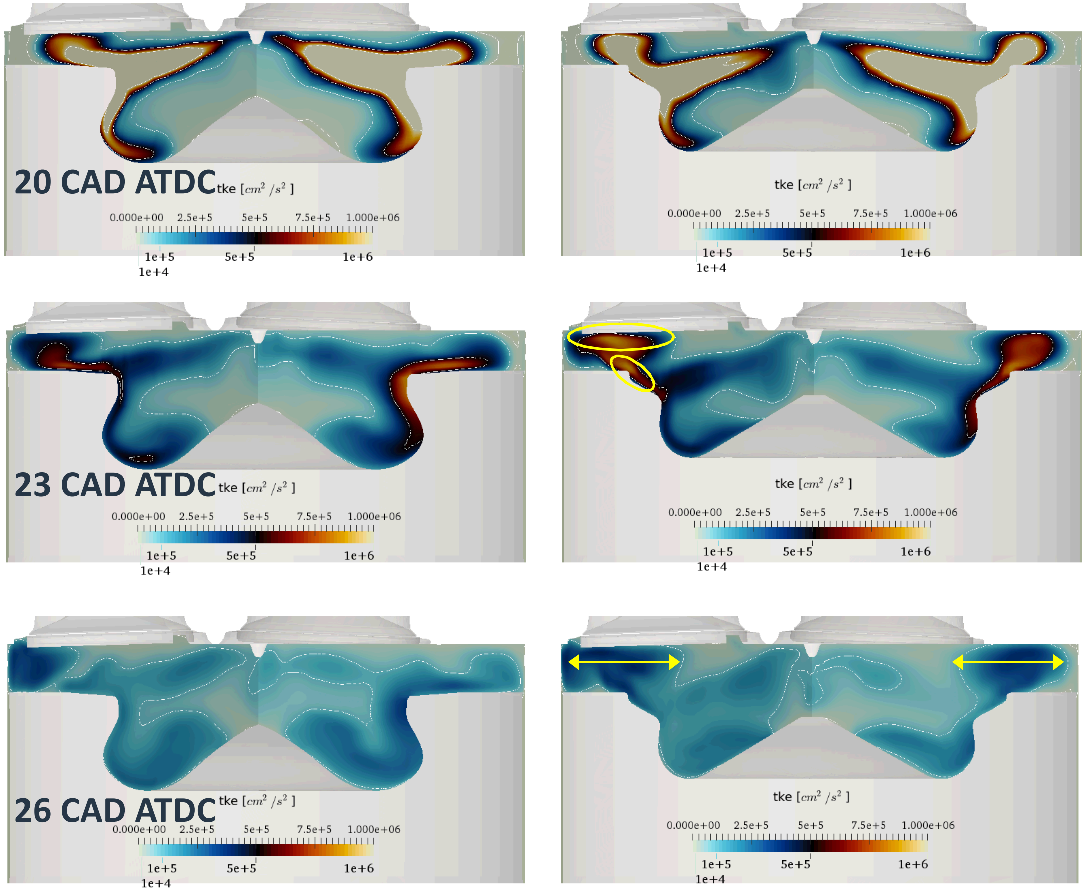
Do CFD simulations predict differences in late-cycle mixing associated with thermal efficiency improvements?



For the intermediate main injection timing, jet-step interactions create significant turbulence in the squish region that persists late in the cycle

- 20 CAD ATDC: shortly before CA50
  - Similar turbulent kinetic energy distributions; impingement on cylinder head begins with stepped-lip piston
- 23 CAD ATDC: shortly after CA50
  - Stepped-lip: deflection at step, impingement on cylinder head create significant turbulence
  - TKE distributions in the bowls are comparable
- 26 CAD ATDC: after CA50
  - Enhanced turbulence persists above the step and spreads due to impingement on the head, formation of upper toroidal vortex

Intermediate injection timing

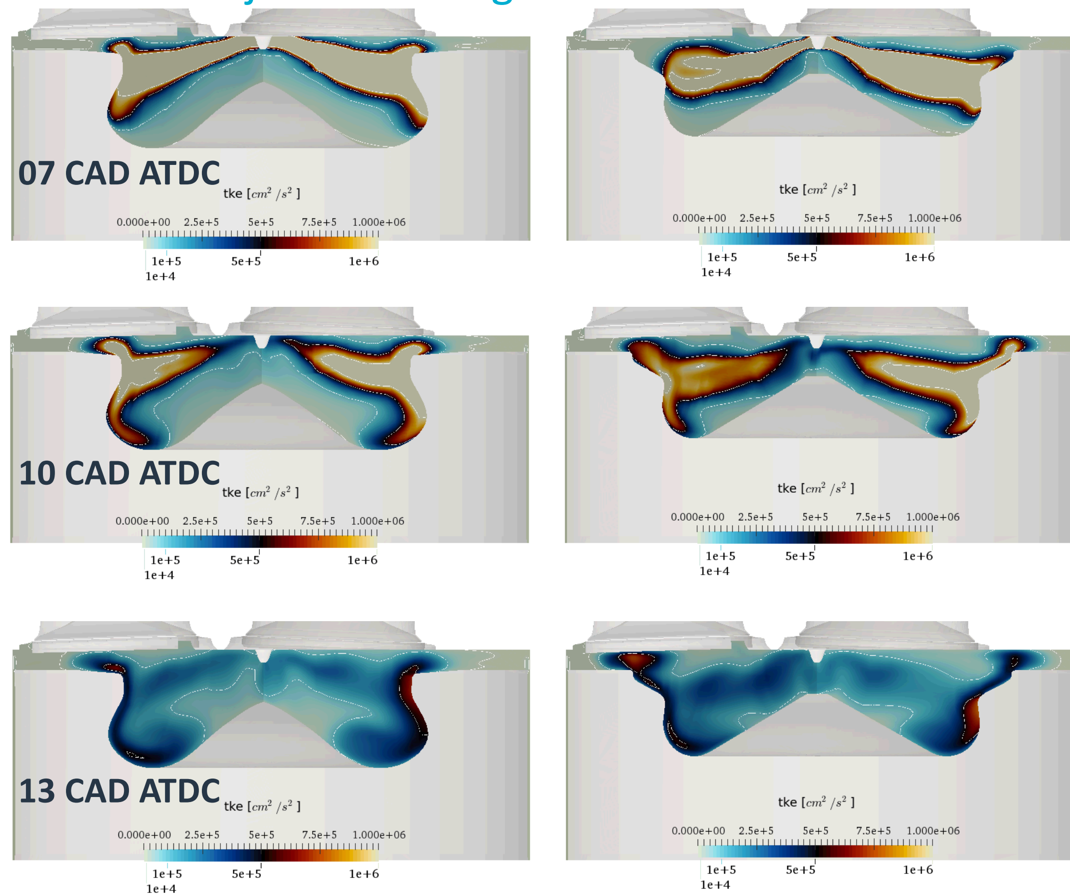


During engine testing with the stepped-lip piston, a ring of deposited soot was observed on the cylinder head above the step region for this injection timing

For the <u>near-TDC main injection timing</u>, robust, long-lived flow structures beneficial for mixing do not form above the step region

- 07 CAD ATDC: ~CA20
  - Similar turbulent kinetic energy distributions; impingement on bowl rims has just begun
- 10 CAD ATDC: ~CA40
  - TKE distributions are comparable
- 13 CAD ATDC: shortly after CA50
  - Stepped-lip: impingement on the cylinder head leads to less spreading than with the intermediate injection timing; TKE is concentrated in a small annular region above the lip
  - The limited step-head spacing appears to inhibit flow structures that promote spreading

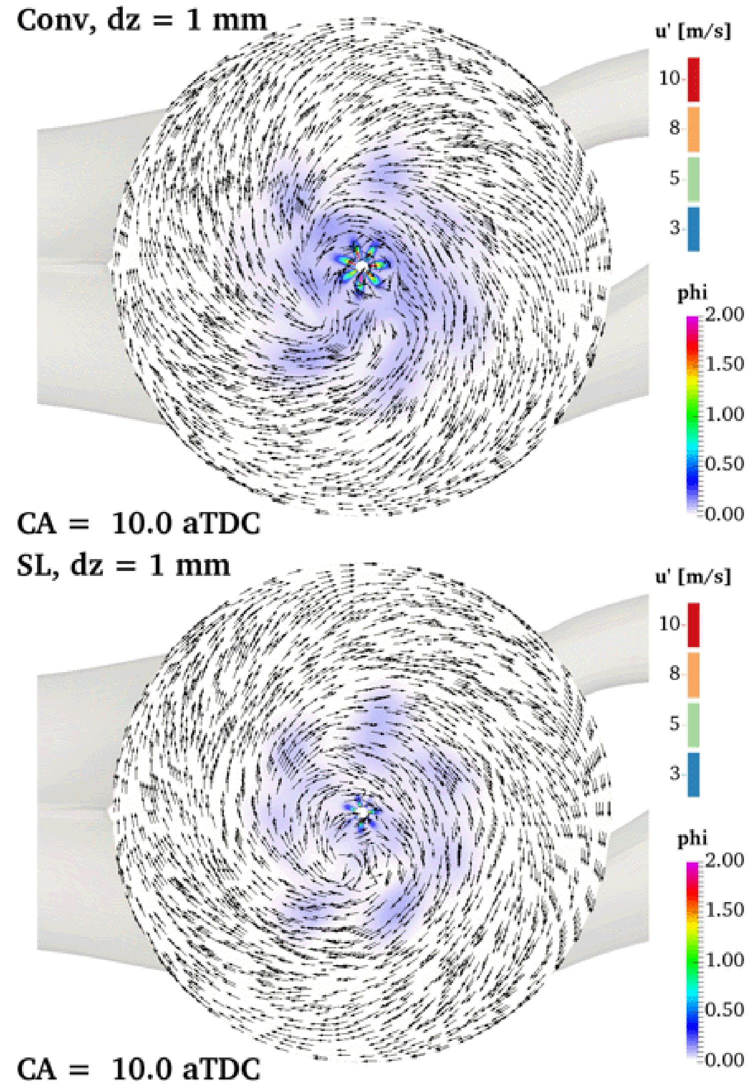
Near-TDC injection timing



For the <u>intermediate injection timing</u>, the stepped-lip piston changes jet-head interactions: azimuthal and radial spreading are enhanced

- Early spray development
  - Jets propagate outward toward the bowl rim
  - Greater upward deflection with conventional bowl (Coanda effect, stronger bowl vortex)
- Jet behavior in the squish region
  - Conventional: modest spreading of jet heads, transition into swirling flow; jets remain separated
  - SL: impingement on cylinder head leads to more rapid spreading of jet heads, both radially and tangentially
- Late-cycle behavior
  - Conventional: mixture remains in squish region and swirl motion is slow
  - Stepped-lip: upper toroidal vortex transports mixture inward; mixture is more evenly distributed over a larger portion of the cutting plane

Swirl plane 1mm below the head



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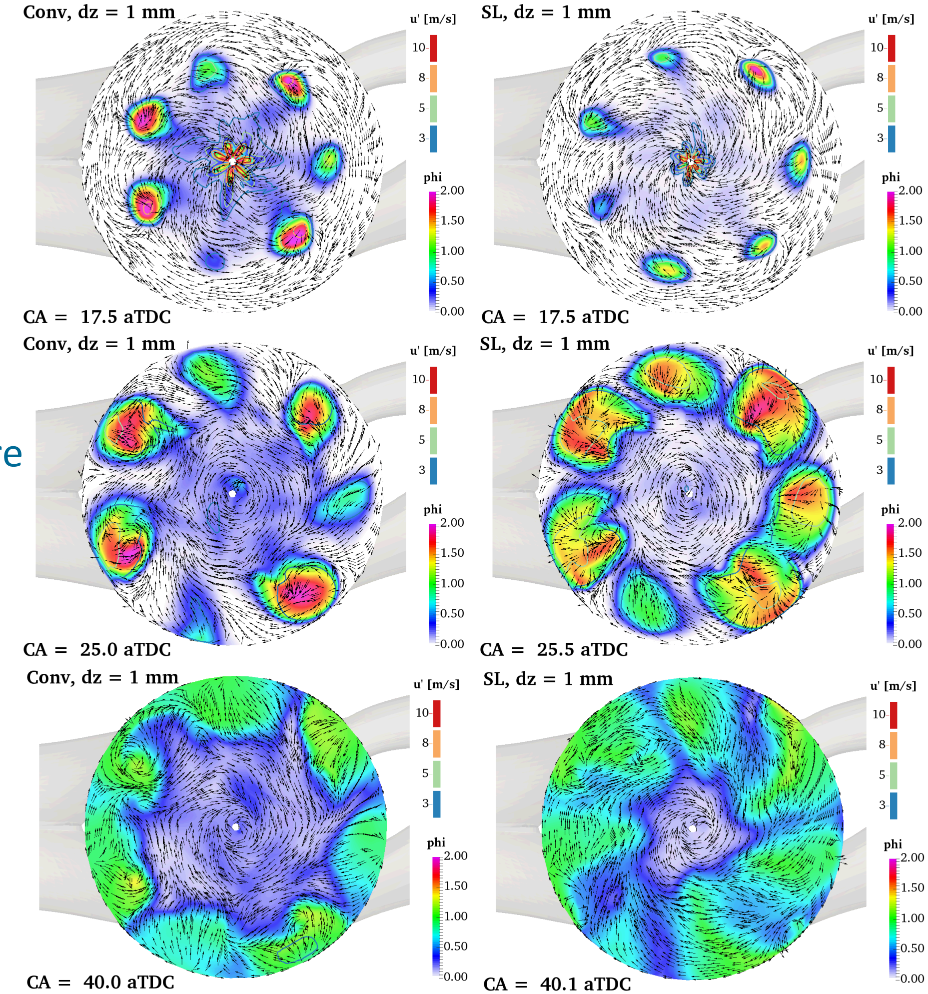

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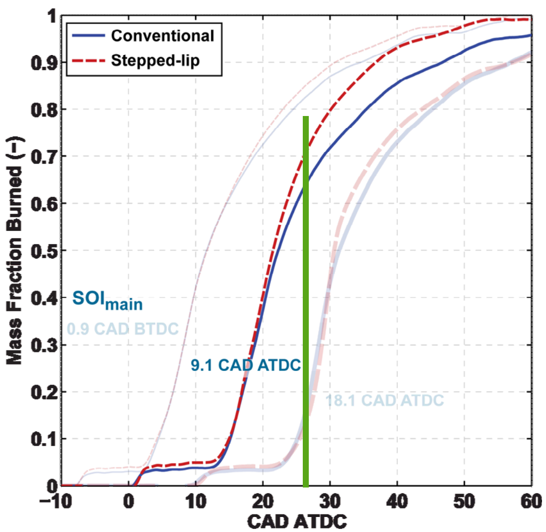
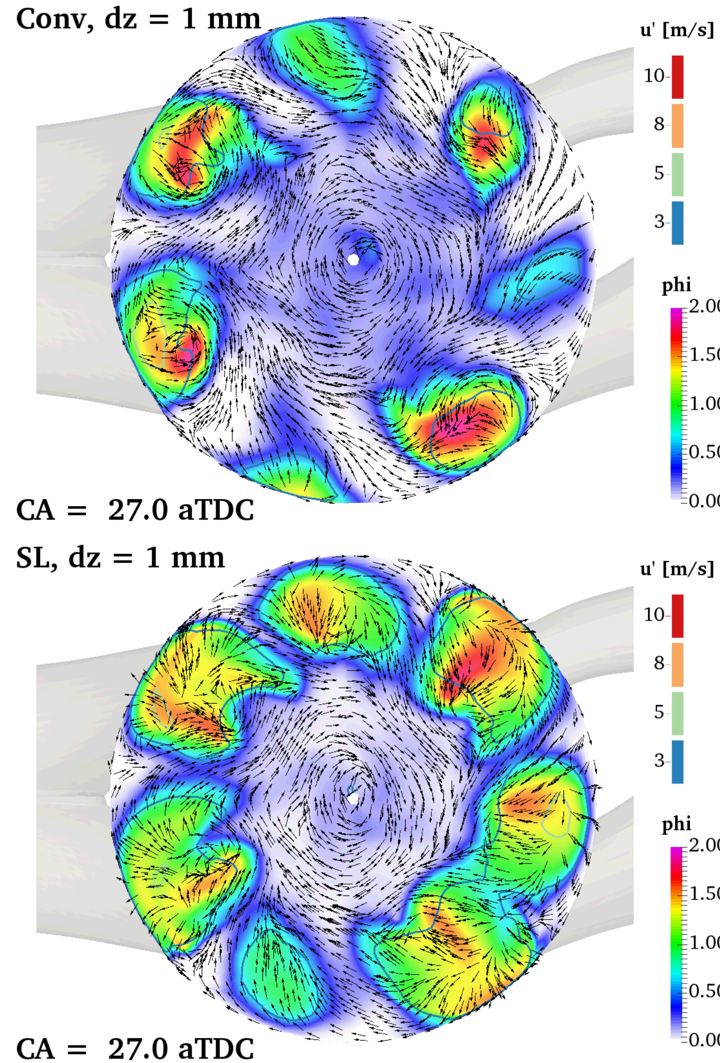
For the <u>intermediate injection timing</u>, mixture and turbulence are spread over a larger region above the stepped-lip bowl

- 27 CAD ATDC: ~CA70; enhanced late-cycle mixing is expected to occur with the stepped-lip bowl based on experiments



- Recall that with the stepped-lip piston for this injection timing, the majority of the fuel is redirected upward at the step
- With the stepped-lip bowl, jet impingement on head leads to significant spreading of mixture, but also of turbulence

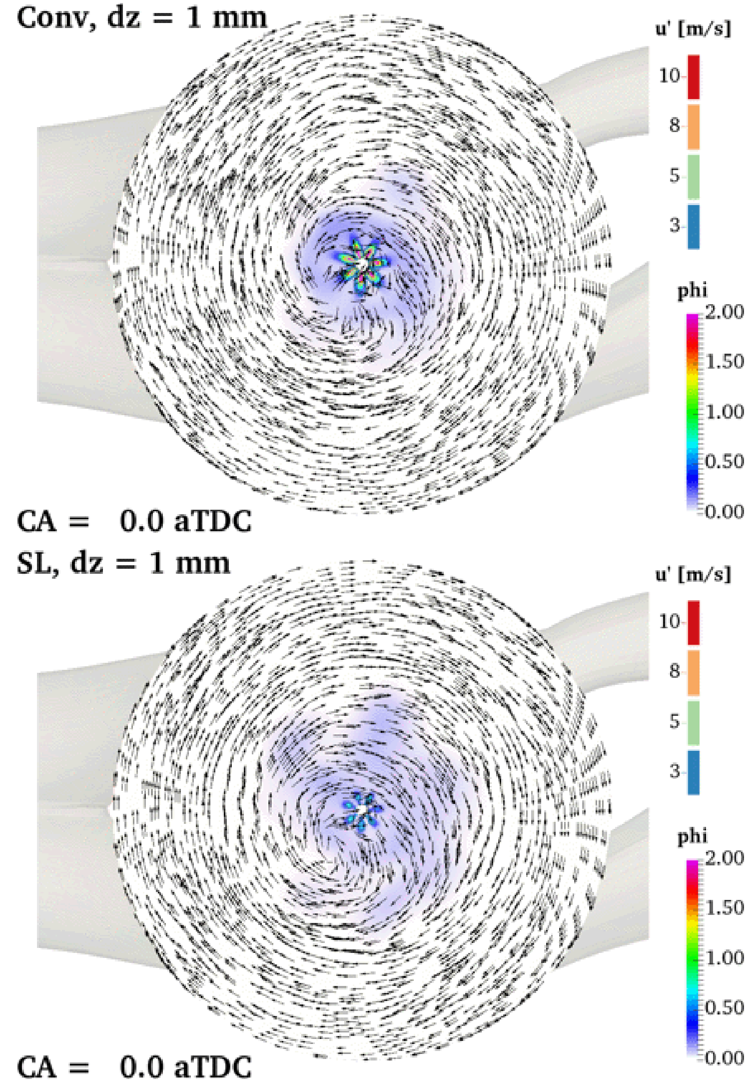
Swirl plane 1mm below the head



For the near-TDC injection timing,

- Early spray development
  - Stronger interaction with bowl rim for conventional bowl; greater tangential spreading and slow penetration into squish
  - Greater upward deflection with conventional bowl (Coanda effect, stronger bowl vortex)
- Jet behavior in the squish region
  - Conventional: slow penetration; jet heads merge and continue to be transported by swirl
  - SL: larger proportion of fuel in the squish; impingement on cylinder head causes jet heads to spread
- Late-cycle behavior
  - Conventional: squish mixture becomes leaner, toroidal vortex in bowl carries mixture upward in the center of the chamber
  - Stepped-lip: squish mixture is primarily transported by swirl – no upper toroidal vortex to promote inward motion

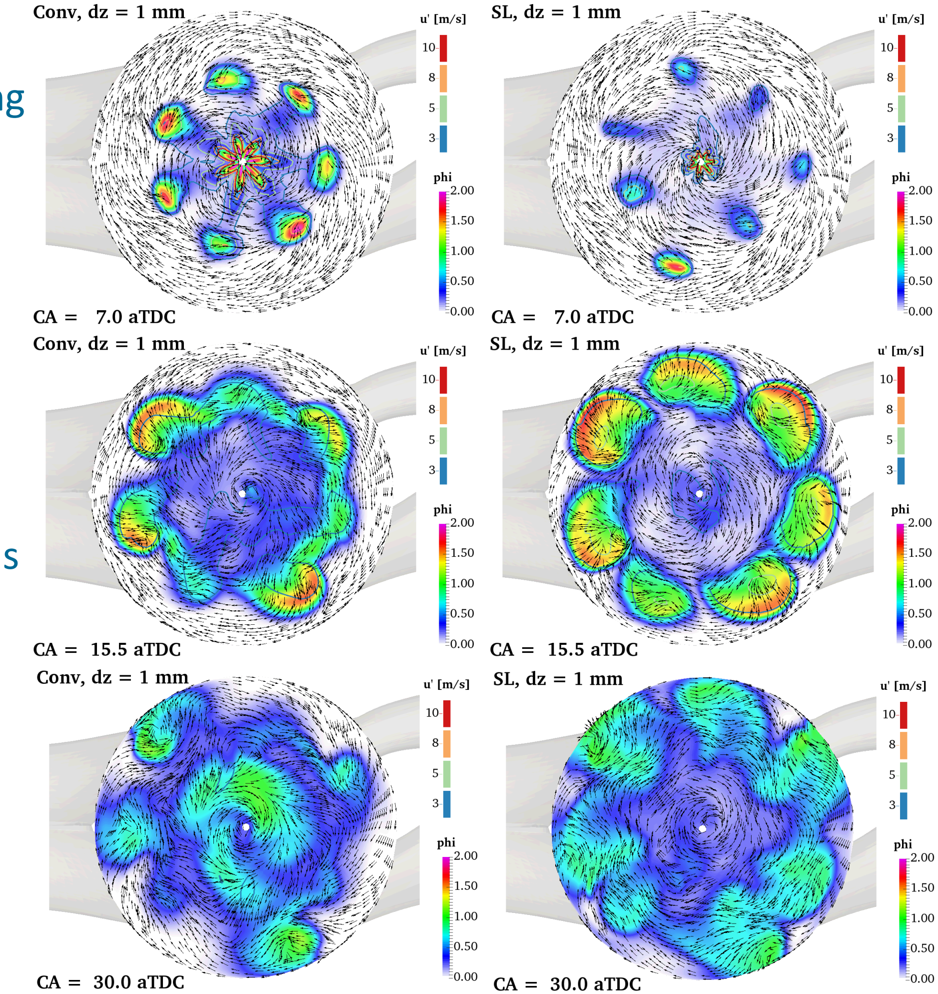
Swirl plane 1mm below the head



For the near-TDC injection timing,

- Early spray development
  - Stronger interaction with bowl rim for conventional bowl; greater tangential spreading and slow penetration into squish
  - Greater upward deflection with conventional bowl (Coanda effect, stronger bowl vortex)
- Jet behavior in the squish region
  - Conventional: slow penetration; jet heads merge and continue to be transported by swirl
  - SL: larger proportion of fuel in the squish; impingement on cylinder head causes jet heads to spread
- Late-cycle behavior
  - Conventional: squish mixture becomes leaner, toroidal vortex in bowl carries mixture upward in the center of the chamber
  - Stepped-lip: squish mixture is primarily transported by swirl – no upper toroidal vortex to promote inward motion

Swirl plane 1mm below the head



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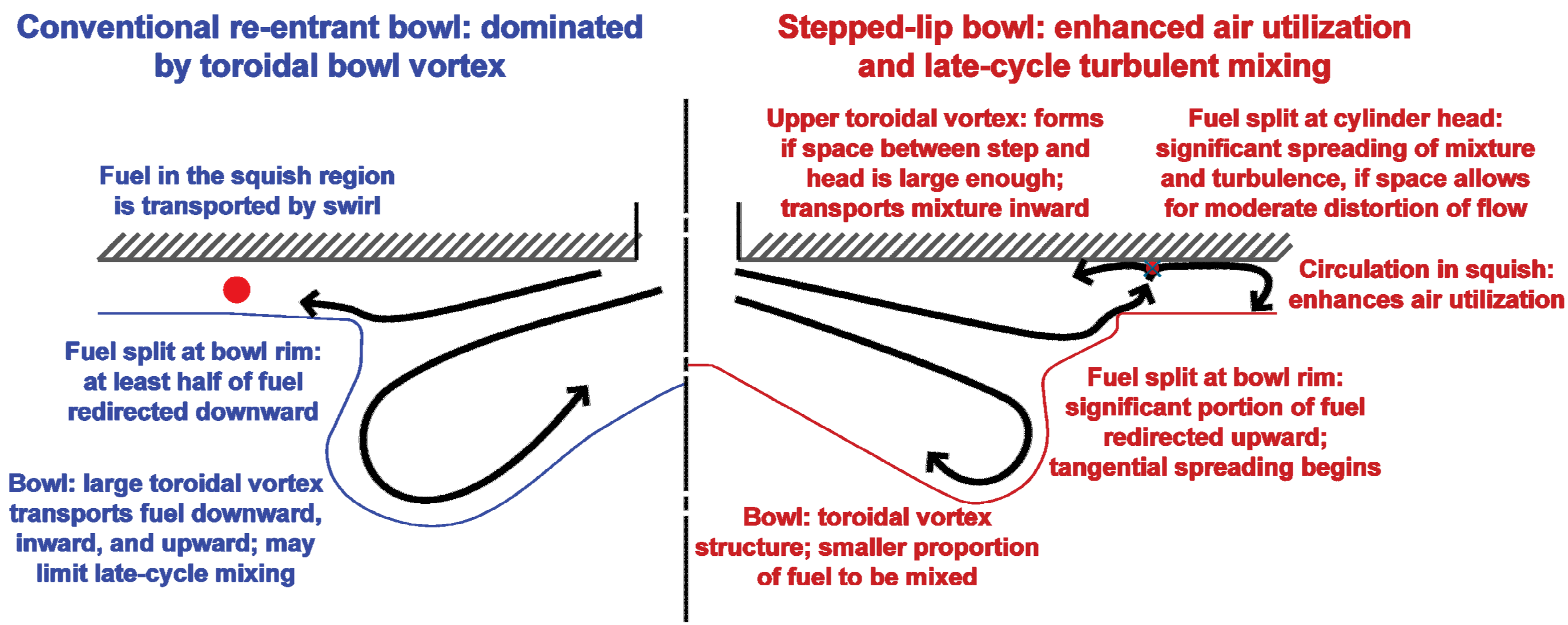
Summary: theory of late-cycle mixing behavior

- Conceptual models in development to explain the observed late-cycle mixing behavior
- Jet impingement, fuel splitting, and vortex dynamics appear to play key roles to enhance:
  - Air utilization
  - Late-cycle mixing



ECN Collaboration

- Sandia single-cylinder, small-bore engine geometry now available on the ECN website
  https://ecn.sandia.gov/engines/engine-facilities/small-bore-diesel-engine/

- STL files for intake/exhaust runners, surge tanks, head / ports, combustion chamber
  - Thanks to GM for permission to share the GM 1.9L engine geometry
  - Thanks to Federico Perini for providing geometry files

- Stepped-lip piston bowl geometry also available on ECN website
  - Thanks to Ford for permission to share this bowl profile

- Boundary conditions and experimental data will soon be made available:
  - Bowl geometry study: thermodynamic data, injection rates, optical data
  - Close-coupled pilot study: thermodynamic data, injection rates, optical data

Acknowledgments

- Technical input and project guidance
  - Alok Warey, Dick Peterson (GM)
  - Eric Kurtz (Ford)

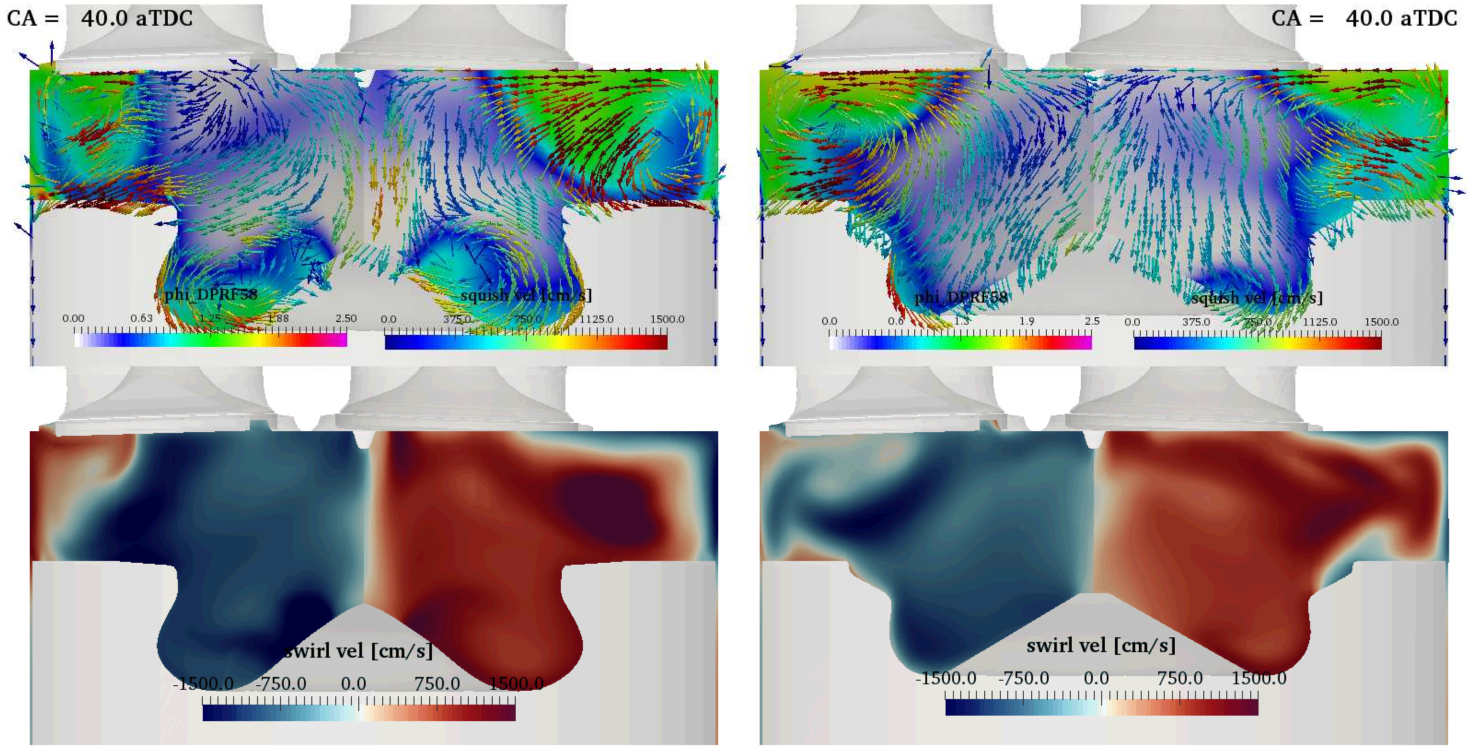
- Laboratory operations assistance
  - Tim Gilbertson (Sandia)

- Financial support: DOE program
  - Gurpreet Singh
  - Leo Breton

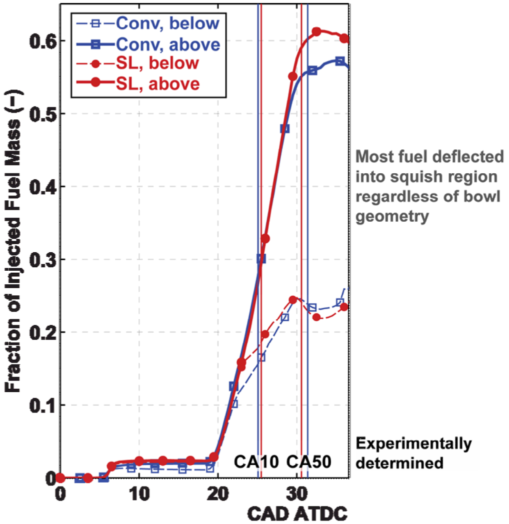
Thank you for your attention

Questions?

Late injection timing: quantifying fuel splitting



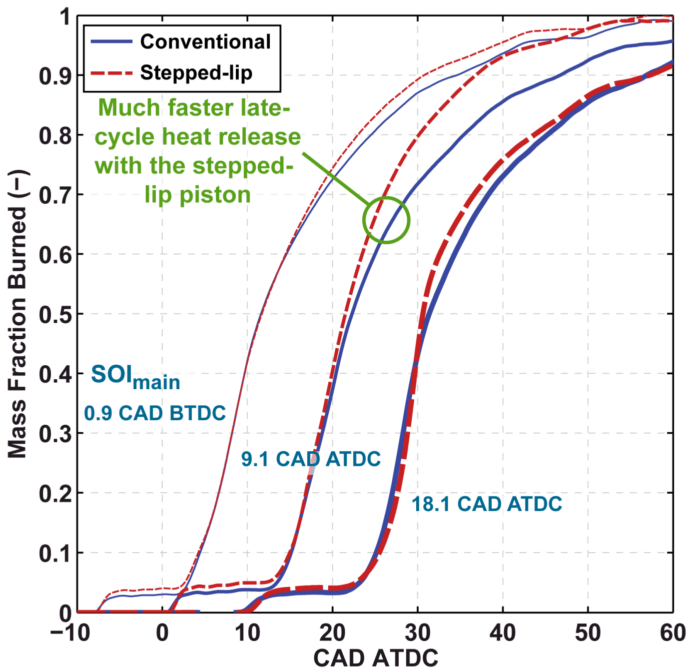
- Toroidal vortex structure appears more organized in the conventional bowl
- Fuel splitting: little difference between bowls
  - Majority of fuel remains in the squish region



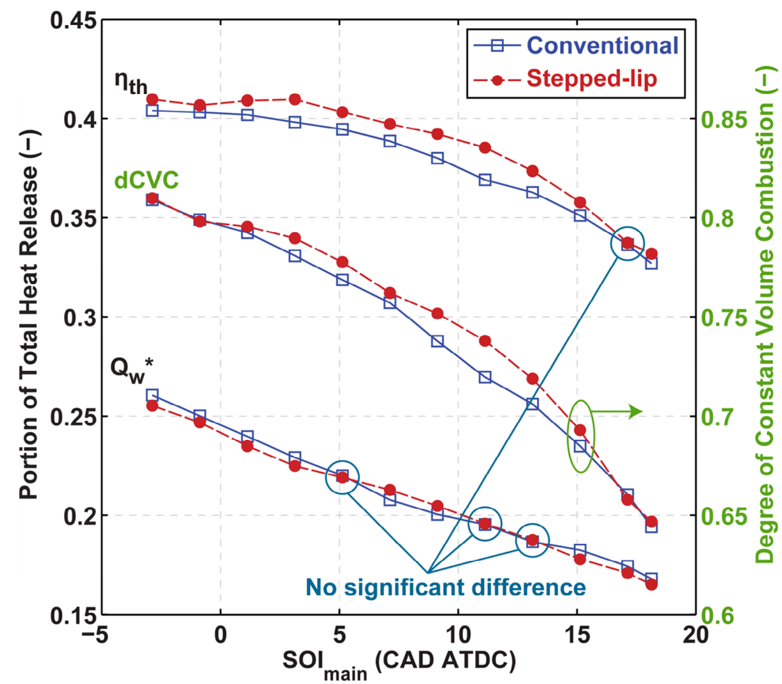
Thermodynamic analysis – what is responsible for the increase in thermal efficiency with the stepped-lip piston?

With the stepped-lip piston:

- Late-cycle heat release is enhanced for intermediate main injection timings (3-13 CAD ATDC)
- Whether normalized wall heat loss increases or decreases depends on injection timing



Bowl geometry can have a profound impact on late-cycle heat release



Thermal efficiency gains with the stepped-lip piston are greatest for main injection timings between 3 and 13 CAD ATDC

Thermodynamic analysis – what is responsible for the increase in thermal efficiency with the stepped-lip piston?

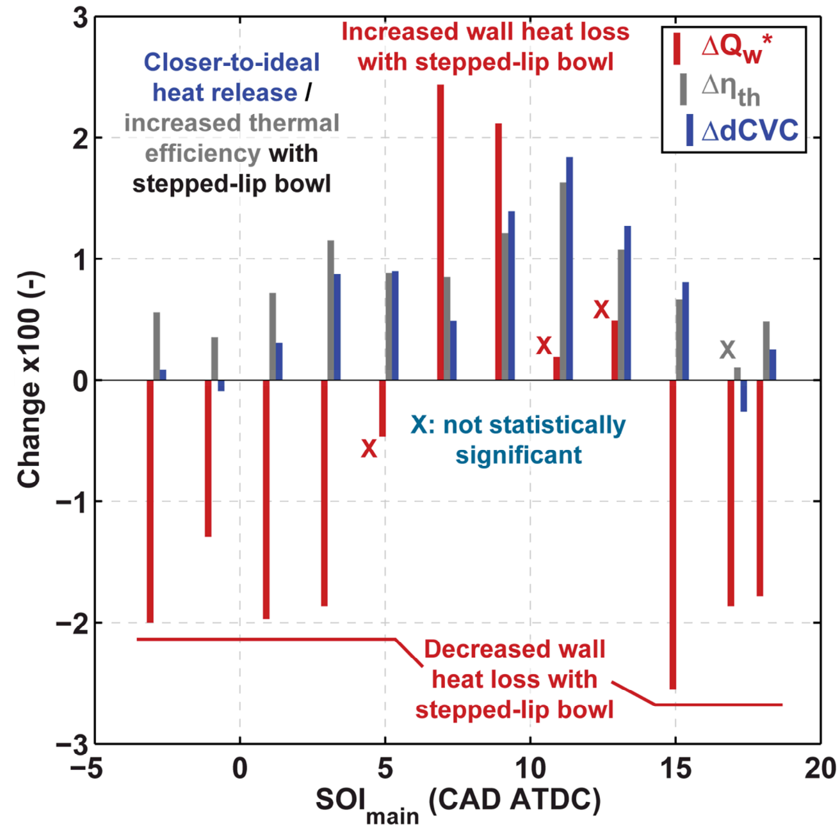
- Integrated wall heat loss (IVC-EVO) normalized by total heat released:

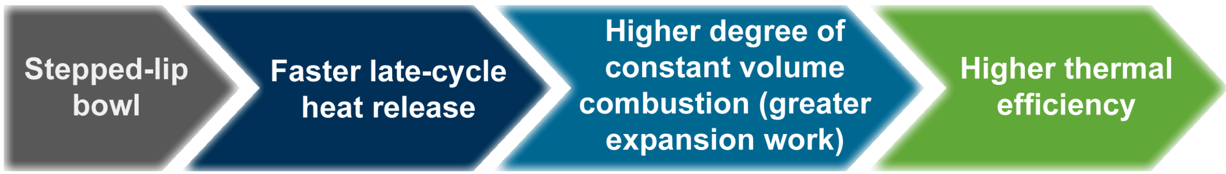
$$Q_w^* = \frac{Q_w}{Q_{hr}} = \frac{\int_{IVC}^{EVO} \frac{dQ_w}{d\theta} d\theta}{\max\left(\int_{SOI}^{EVO} \frac{dQ_{hr}}{d\theta} d\theta\right)}$$

- Boundary work (IVC-EVO) normalized by total heat released:

$$\eta_{th} = \frac{W}{Q_{hr}} = \frac{\int_{V_{IVC}}^{V_{EVO}} PdV}{\max\left(\int_{SOI}^{EVO} \frac{dQ_{hr}}{d\theta} d\theta\right)}$$

- Changes in thermal efficiency correlate most closely with changes in the degree of constant volume combustion
    - Improved late-cycle mixing has a greater impact on efficiency than reduced wall heat loss

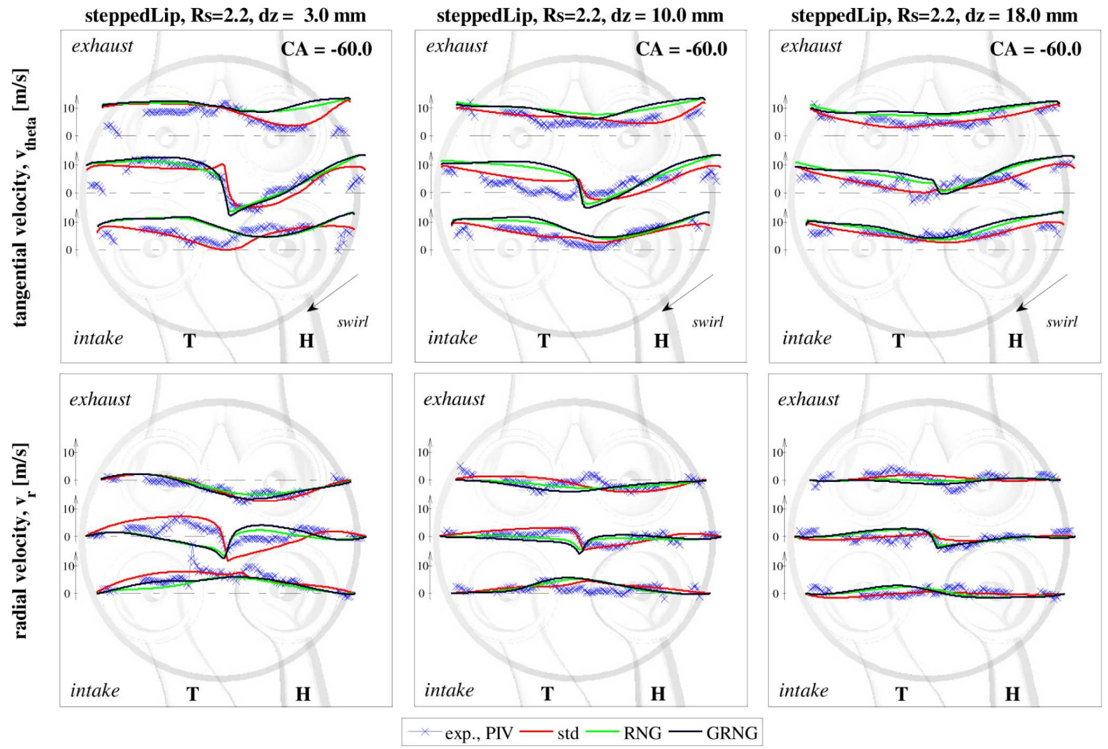




CRF

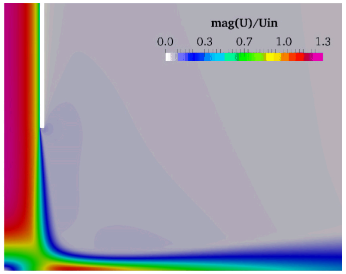
Various 2-equation turbulence models have been evaluated using PIV data from the SNL light-duty optical diesel engine

No turbulence model predicts the experimental cold-flow data perfectly, but the standard k-ε model is slightly more accurate than the RNG and GRNG models at predicting compression-stroke flow topology.

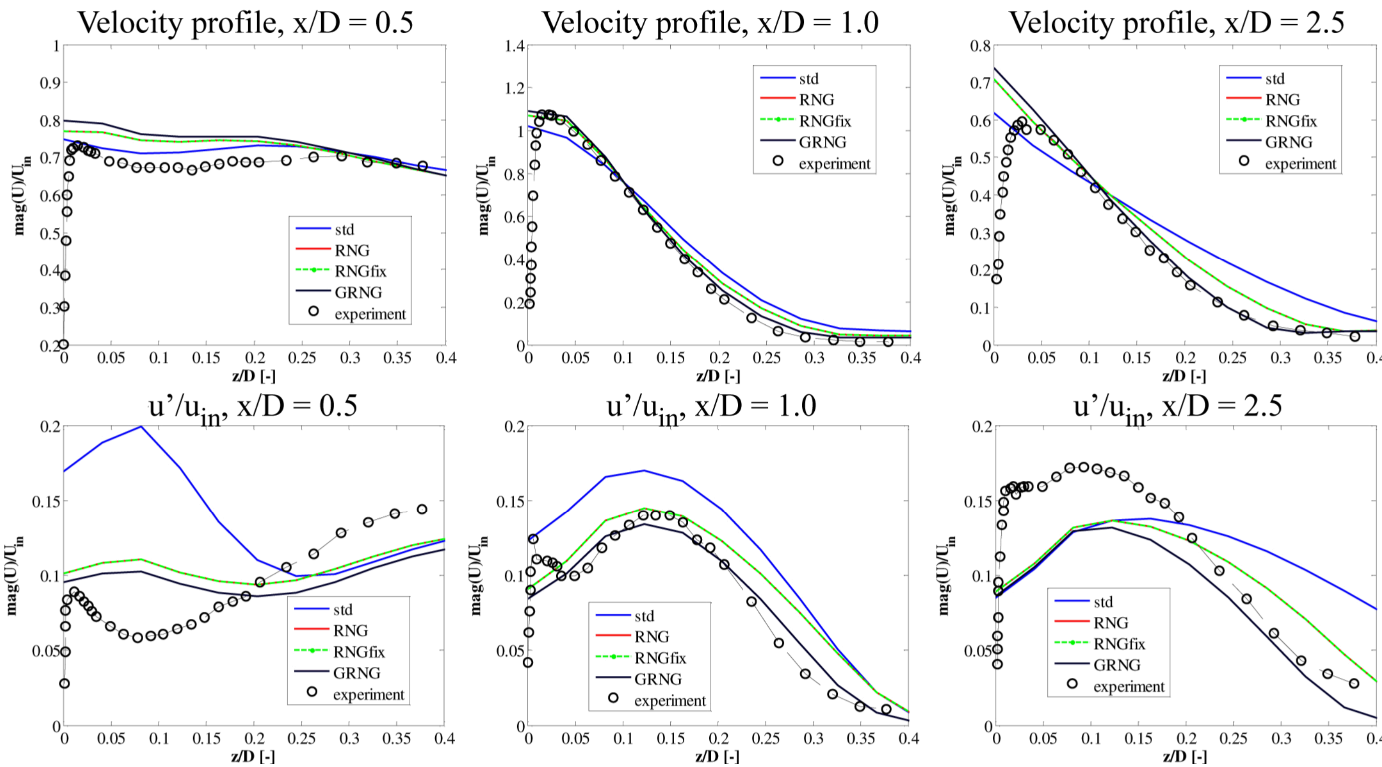


For details, see Perini, F., Zha, K., Busch, S., and Reitz, R., "Comparison of Linear, Non-Linear and Generalized RNG-Based k-epsilon Models for Turbulent Diesel Engine Flows," SAE Technical Paper 2017-01-0561, 2017, doi:10.4271/2017-01-0561.

Various 2-equation turbulence models have been evaluated using canonical flows such as a gas jet impinging on a plate



The GRNG turbulence model provides the most accurate velocity-profile predictions and reasonable predictions of velocity fluctuations near the jet.

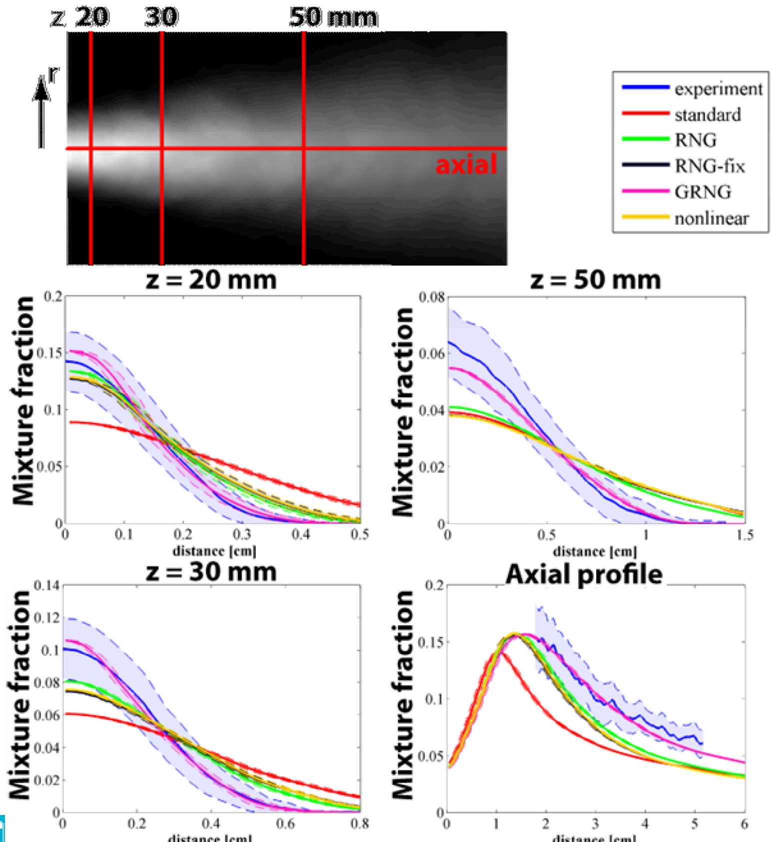


The RNG and GRNG models both perform reasonably well for all simulated diesel engine-like flow conditions

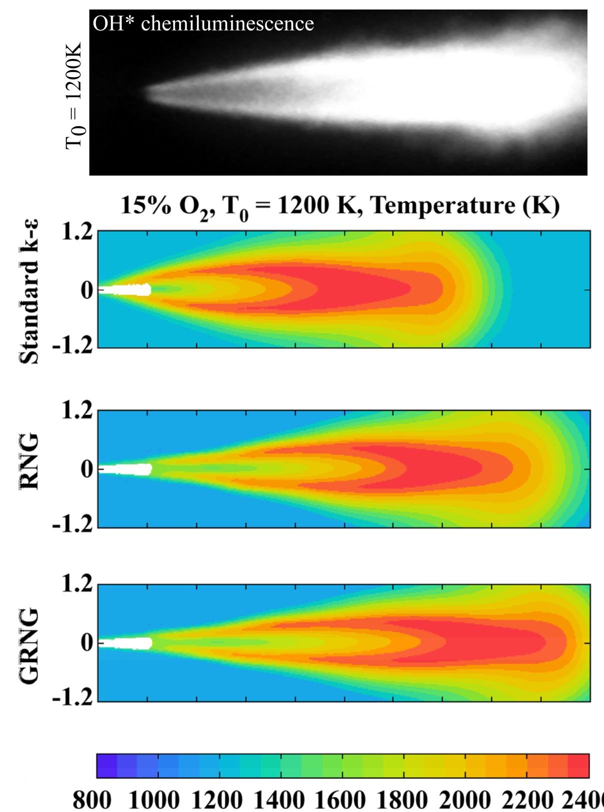
Various 2-equation turbulence models are evaluated with ECN Spray A data

The Generalized RNG (GRNG) turbulence model (a product of SNL-UW collaboration) has been determined to produce the best accuracy trade-off between cold engine flow and jet flow / spray combustion based on comparisons with state-of-the-art ECN data.

Mixture formation is better predicted with the GRNG turbulence model



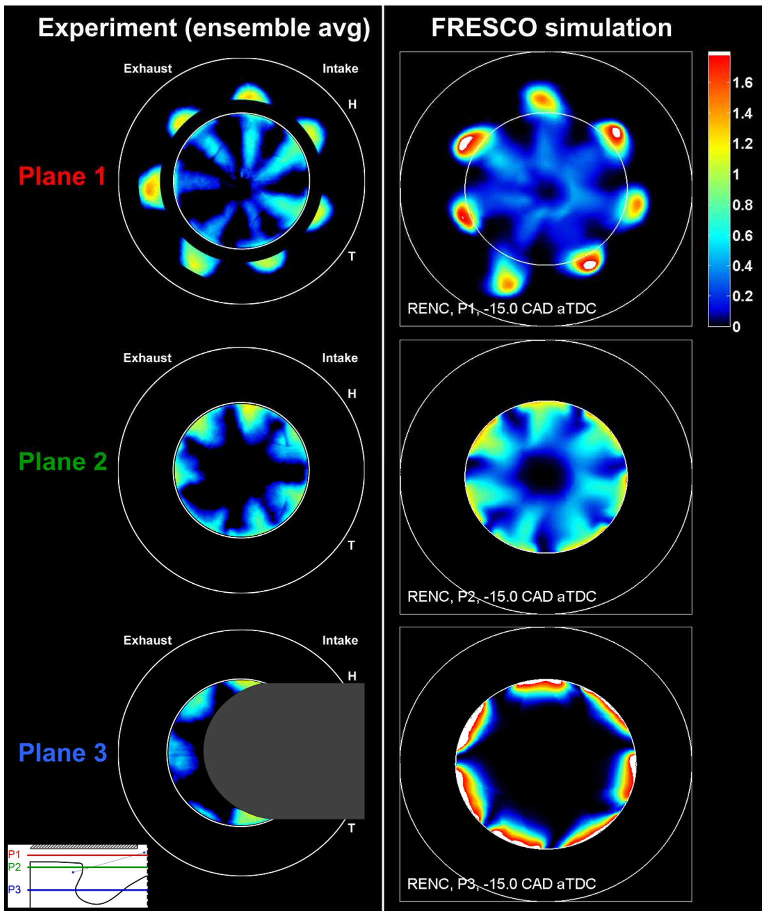
The GRNG model yields the most accurate flame structure predictions

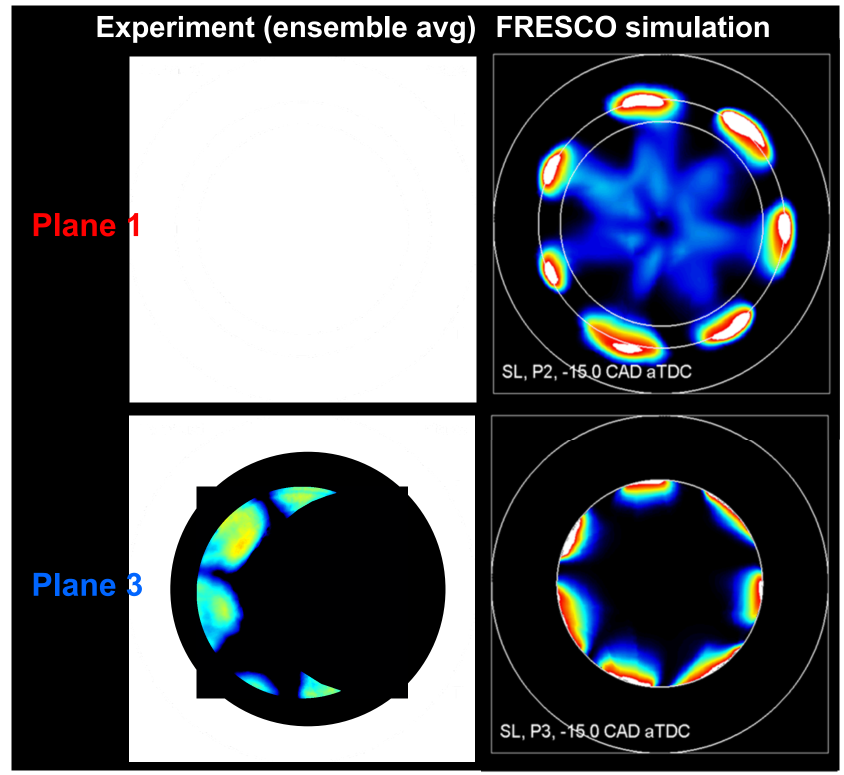


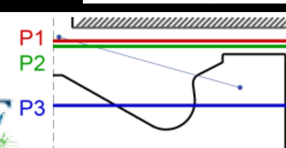
Comparisons of PLIF data with both bowls

Conventional bowl: jet penetration into bowl reasonably well captured; phenomenology well predicted

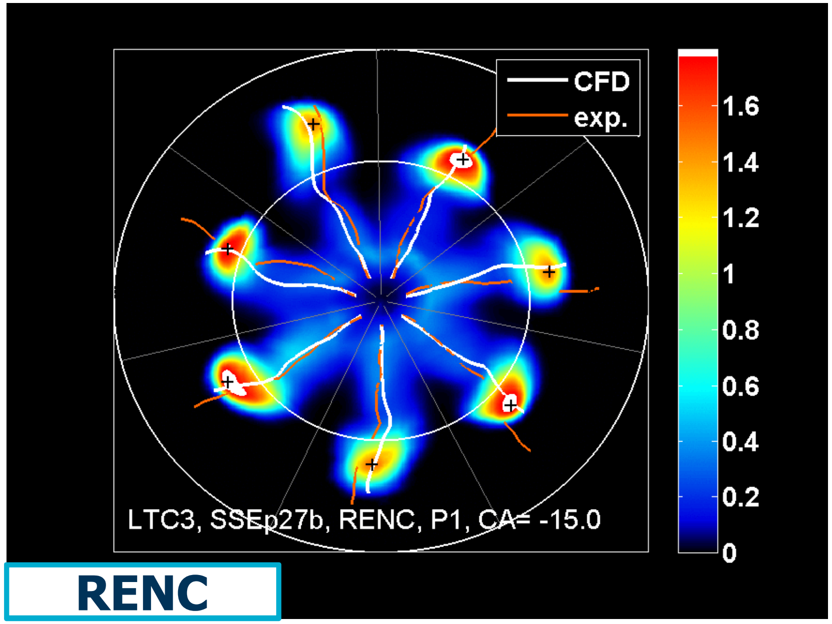
Stepped-lip bowl: good qualitative agreement; questions remain about vortex dynamics resulting from jet-step interactions

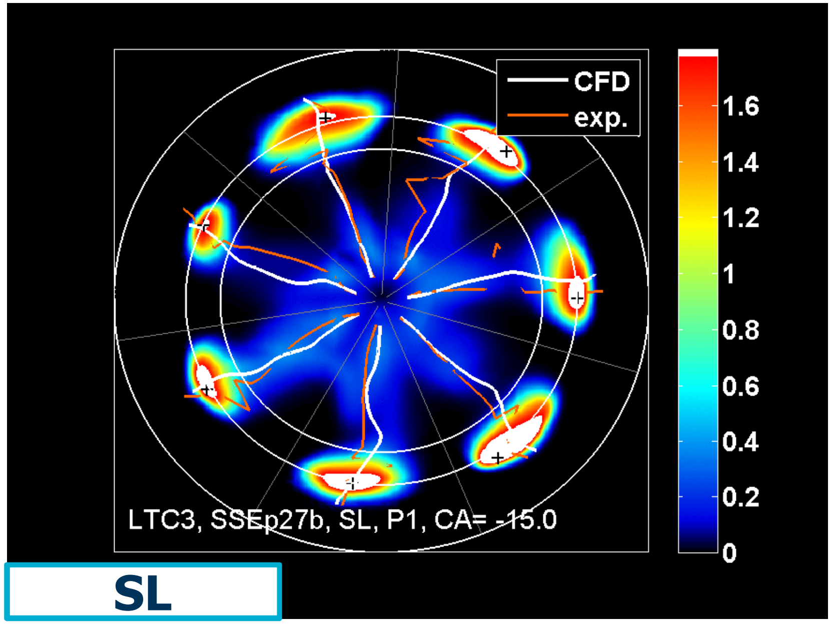






Jet-swirl interactions / jet-bowl interactions (from AEC presentation)





- Jet deflection and rotation due to swirl are well captured in bowl & squish regions
- Mixture forming above the step is broadened by presence of the step → peak phi's unaffected
- Jet deviation phenomenon at the rim ← turbulence modeling