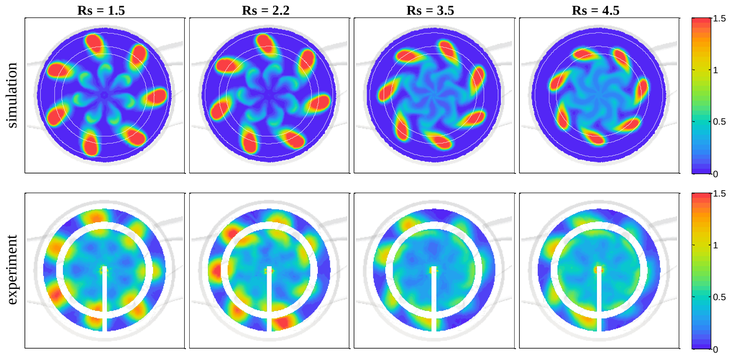
Study of In-cylinder Swirl Flow Structures using Principal Component Analysis

Federico Perini, Rolf D. Reitz, Paul C. Miles

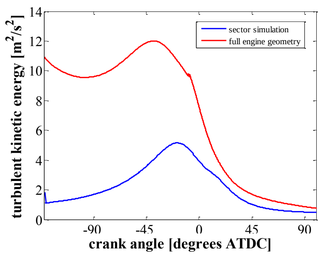
Funding Sponsor – Sandia National Laboratories

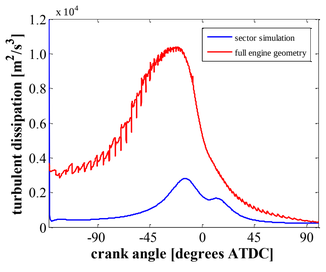
Motivation

- CO and UHC emissions in light-load partially premixed combustion strategies for light duty engines mainly arise from overly lean mixture forming at the center of the combustion chamber and in the squish region
- Sector mesh simulation can't capture this phenomenon well, even though ignition timing and duration are well captured, thanks to accuate spray modelng at the jet centerline
  - ➢ The sector geometry intrinsically simplifies the flow structure



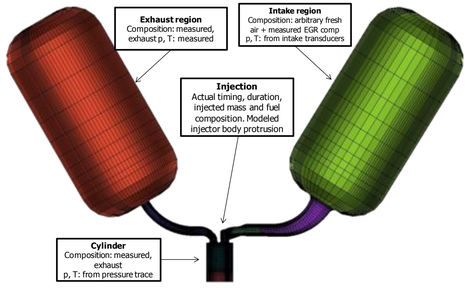
  - ➢ Turbulence development is not properly captured





Full Engine Geometry

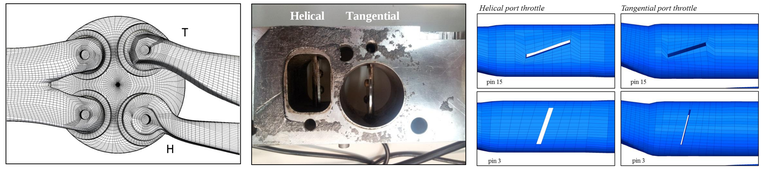
- Full 360 degrees unstructured engine mesh including intake and exhaust runners and plenums of the Sandia 1.9L light duty single cylinder engine facility



- Detailed compositional and thermophysical initial/time-varying boundary conditions
- Adjustable swirl generation plates in the intake runner modeled using cell deactivation

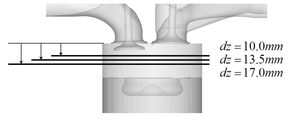
Grid details

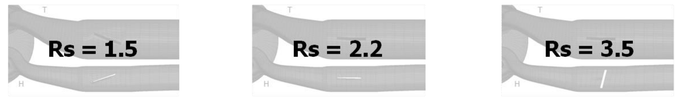
Mesh type	body-fitted hexahedral
Number of cells	682,091
Average cell size near TDC [mm]	0.7



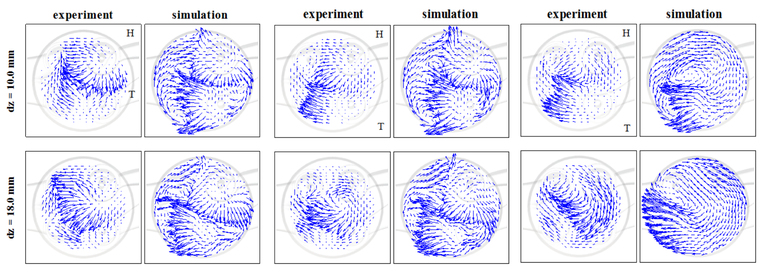
In-cylinder flow modeling

- Comparison with PIV in-cylinder experiments [2]

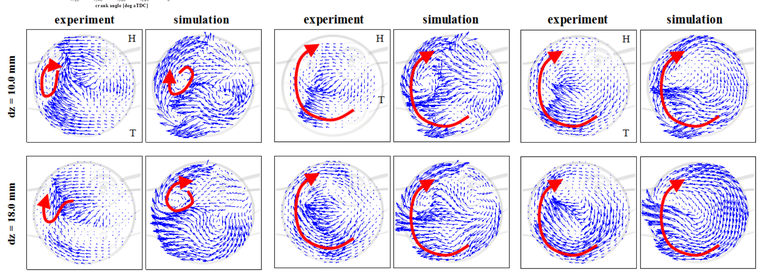




CA -270 → High Rs's have similar structure w/ different bore-scale vortex strength



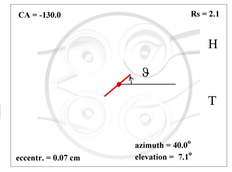
CA -240 → Momentum from T dominates flow structure
→ Recirculating regions at Rs=1.5 due to competition with H

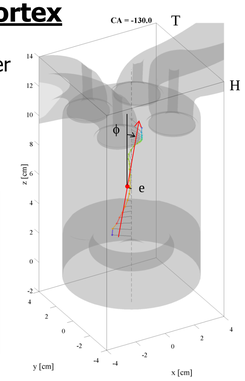


Principal Component Analysis of swirl vortex

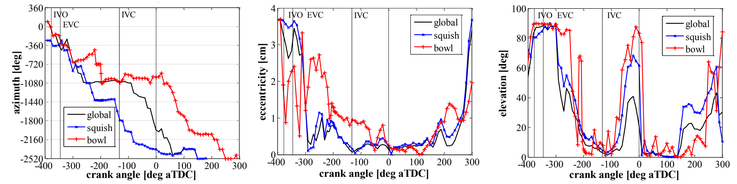
- Dimension reduction of the swirl vortex structure to better understand its implications on local mixture preparation
- 1st principal component = main alignment direction of the swirl center envelope
  - → The axis the vortex would have if **solid-body**
  - → Described thru:

$$\begin{cases} \phi = \text{elevation angle} \in [0, \pi/2] \\ \theta = \text{azimuthal angle} \in [-\pi, \pi] \\ e = \text{center} - \text{of} - \text{mass eccentricity[cm]} \\ \text{Rs} = \text{swirl ratio[-]} \end{cases}$$





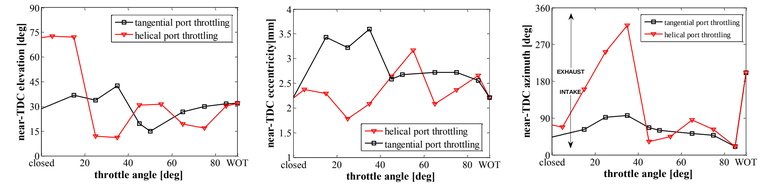
Swirl structure evolution



- Swirl vortex starts forming > -300 aTDC (squish); >-250 aTDC (bowl)
- Tilt is negligible near BDC, accumulates close to TDC
- Fast dissipation of non-symmetric structure after TDC

1) Compression accumulates flow energy into 'noble' storage ← rotational kinetic energy (high Rs) + potential energy (deviation from axial mom. cons. position is a way to store energy by applying some force and enabling an action-reaction effect through gradients, such as what happens in a capacitor, or in a spring).
2) This storage is quicky released back into turbulence as the forcing element (compression) cannot compete anymore against dissipation.

Port throttling effects



Affects:	Principal Components	Global Rs	near-TDC turbulence
Tangential port	↔	↗	↔
Helical port	↗	↗	↔

- Both ports do not change bowl vs. squish discrepancies significantly → role of **piston bowl geometry** and **squish flow**

References

[1] Perini, Miles, Reitz, Computers&Fluids 105, 113-124, 2014.
[2] Perini, Zha, Busch, Miles, Reitz, SAE technical paper 2015-01-1969, 2015.