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Piston Geometry Effects on In-cylinder Swirl Asymmetry in a Light-Duty Optical Diesel Engine

Kan Zha[a], Federico Perini[b], Stephen Busch[a], Cheolwoong Park[c], Rolf D. Reitz[b], Paul C. Miles[a]

[a] Sandia National Laboratories
[b] University of Wisconsin-Madison
[c] Korea Institute of Machinery & Materials

Abstract

In direct-injection light-duty Diesel engines, swirl (bore-scale single rotating vortex around cylinder axis) is needed to promote large-scale transport of fuel vapor and air during injection. Swirl is also crucial for efficient soot oxidation in the late-cycle mixing controlled combustion phase. For twin port design, swirl asymmetry is initiated by the asymmetrical orientation of the intake ports. There exists a great interest in predicting the flow asymmetry in the late compression stroke so as to help deciding the optimum injector location for optimum mixture preparation. Since bowl-in-piston cylinder geometries can be expected to substantially change the in-cylinder flow structures, the experimental assessment of velocity fields (by swirl-plane PIV) needs to be conducted with realistic piston bowl geometries. However, severe image distortion brought by the complex piston geometries is one of the obstacles for accurate velocity measurements. This work presents an update of experimental (planar PIV) and numerical investigations of in-cylinder flow with two piston bowl geometries. Analyses of the distortion-corrected planar PIV results taken for two steady-state swirl ratios of 2.2 and 3.5 yield information about swirl center motion and swirl ratio temporal evolution in the late compression stroke. Both theoretical considerations (1-D simulation) and experimental results show that swirl temporal development with the stepped-lip piston geometry is slower than that with the conventional re-entrant piston geometry in the late compression stroke. This is the joint effect of piston geometry change and the an associated increase in squish height. Further investigation will help clarify the relative importance of these two effects.

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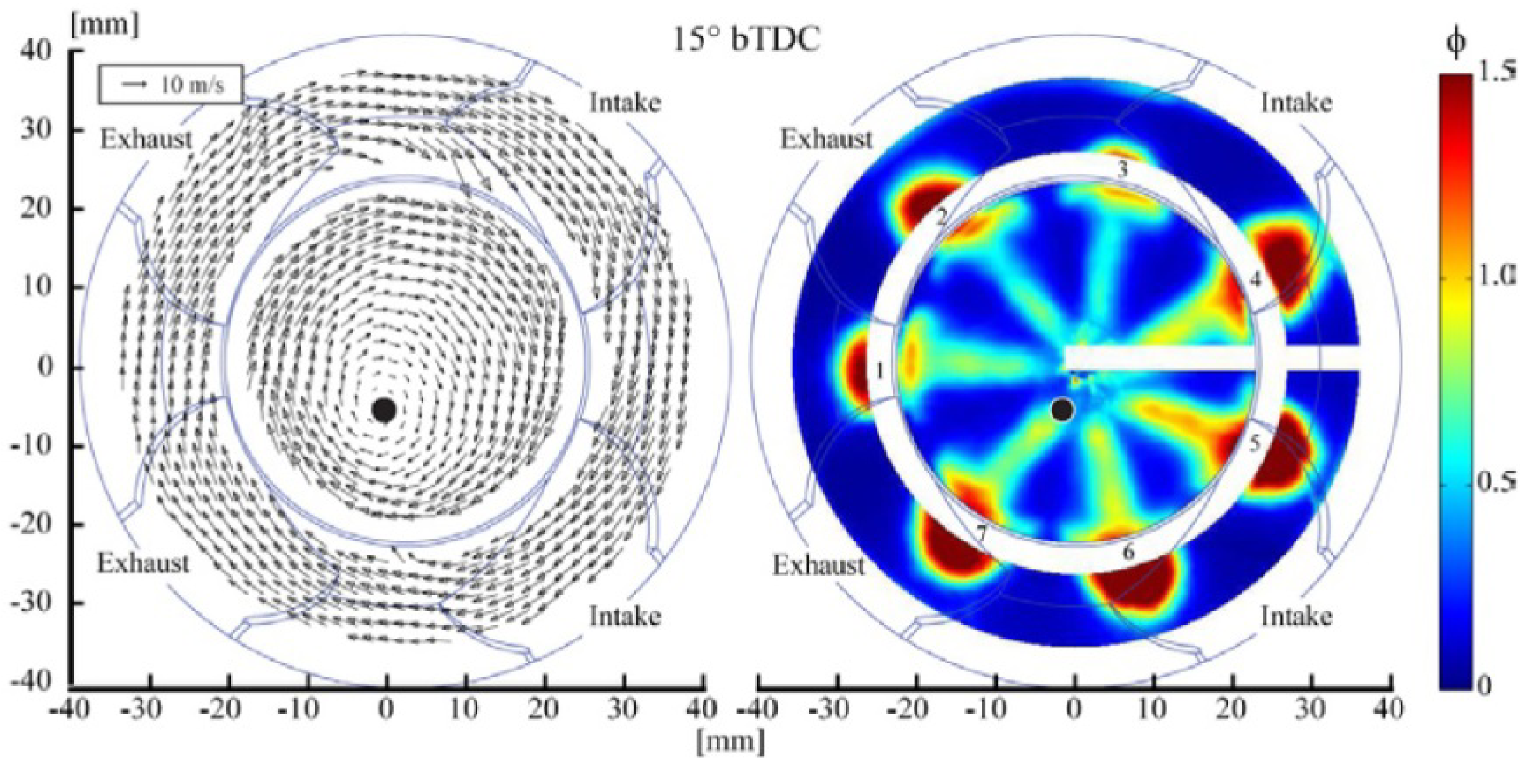
Outline

- Motivation
- Background
- Swirl Development Mechanism: 1-D simulation
- Swirl-Plane PIV Measurement Setup and Test Cases
- Optical Distortion Correction and PIV Tracer Fidelity Check
- Results
  - Geometry Effect on Swirl Development
  - Swirl Center Motion during Compression Stroke
- Summary
- Future Work

Reducing spray asymmetry is considered as one strategy to reduce UHC emissions for light-duty Diesel engines



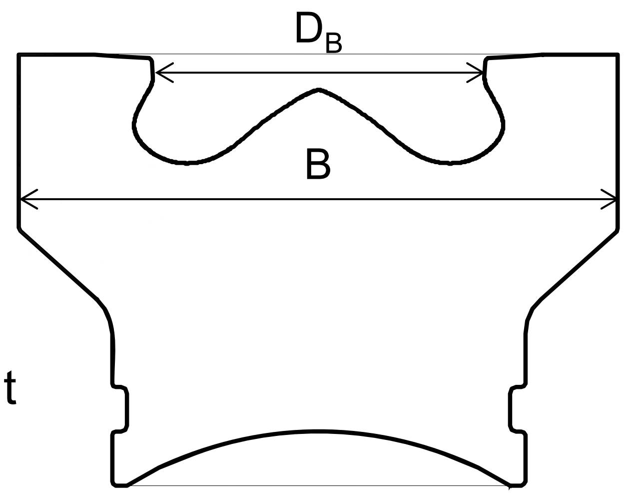
- Spray asymmetry is initiated by the asymmetric mean flow.

[1] Petersen, B., Miles, P., and Sahoo, D., "Equivalence Ratio Distributions in a Light-Duty Diesel Engine Operating under Partially Premixed Conditions," *SAE Int. J. Engines* 5(2):526-537, 2012, doi:10.4271/2012-01-0692.

Background

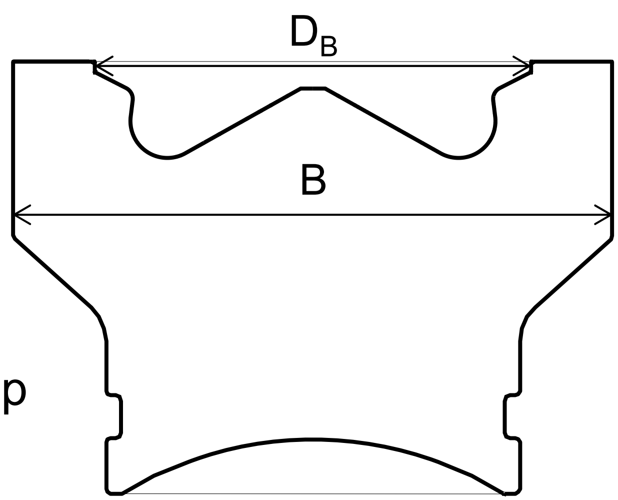
- Two piston bowl geometries with the same bowl volume (0.028L) available for in-cylinder flow asymmetry comparison.

Re-entrant



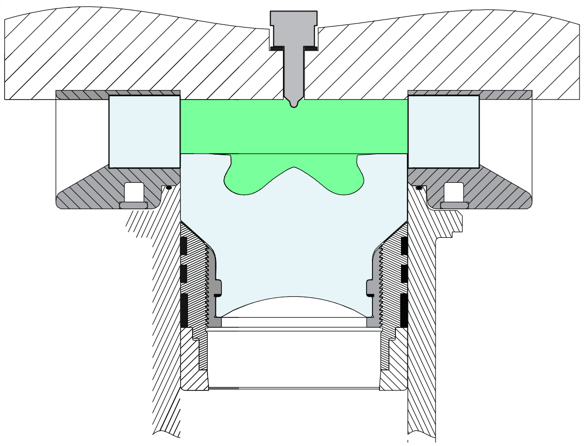
- Squish height (TDC) = 0.711 mm
- Compression ratio = 16.7
- With valve cut-outs
- Bowl to bore ratio: D_B/B=0.55
- Plenty of data available with this geometry matching fired LTC cases

Stepped-lip

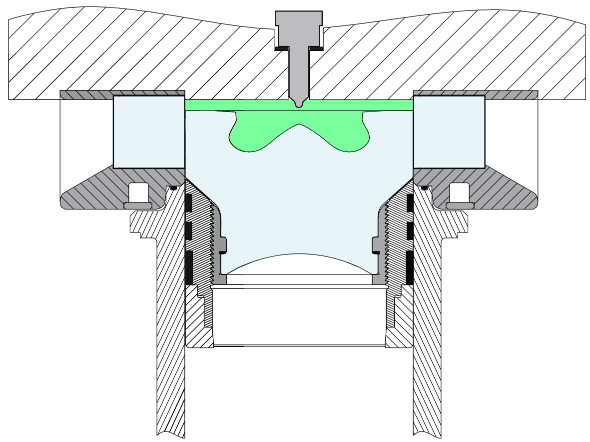


- Squish height (TDC) = 1.346 mm
- Compression ratio = 15.8
- Different optical distortion pattern
- No valve cut-outs
- Bowl to bore ratio: D_B/B=0.73
- 30% higher laser pulse energy
- Optimized laser sheet

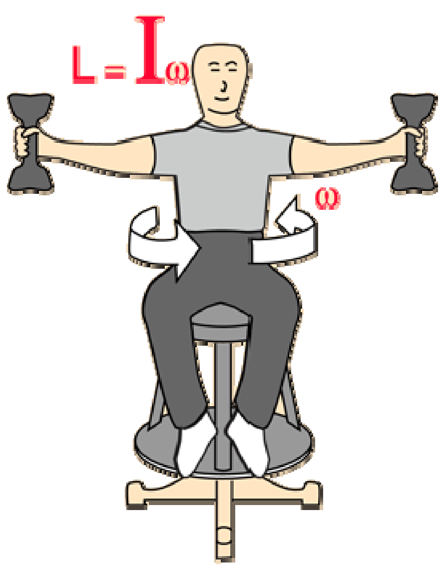
The moment of inertia of the cylinder contents decreases as they are pushed into the piston bowl.

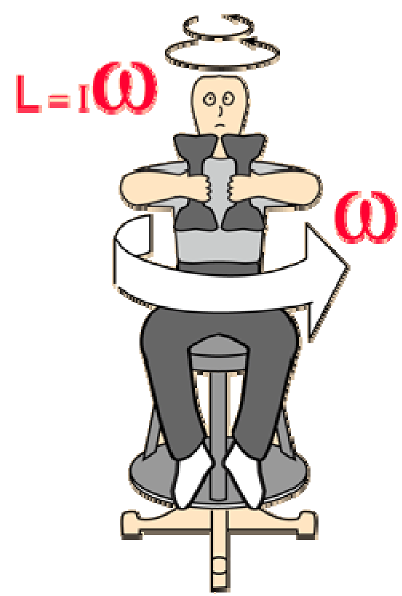


-50⁰aTDC



-20⁰aTDC





- Angular momentum (L) is assumed to be constant after IVC (friction and other losses are neglected).

$$I_z = \int \frac{1}{2}\pi\rho({r_2}^4 - {r_1}^4)dh$$

$$L = Iz\ \omega \approx constant$$

↓ ↑

- Angular velocity (swirl ratio*RPM) will increase to conserve angular momentum.

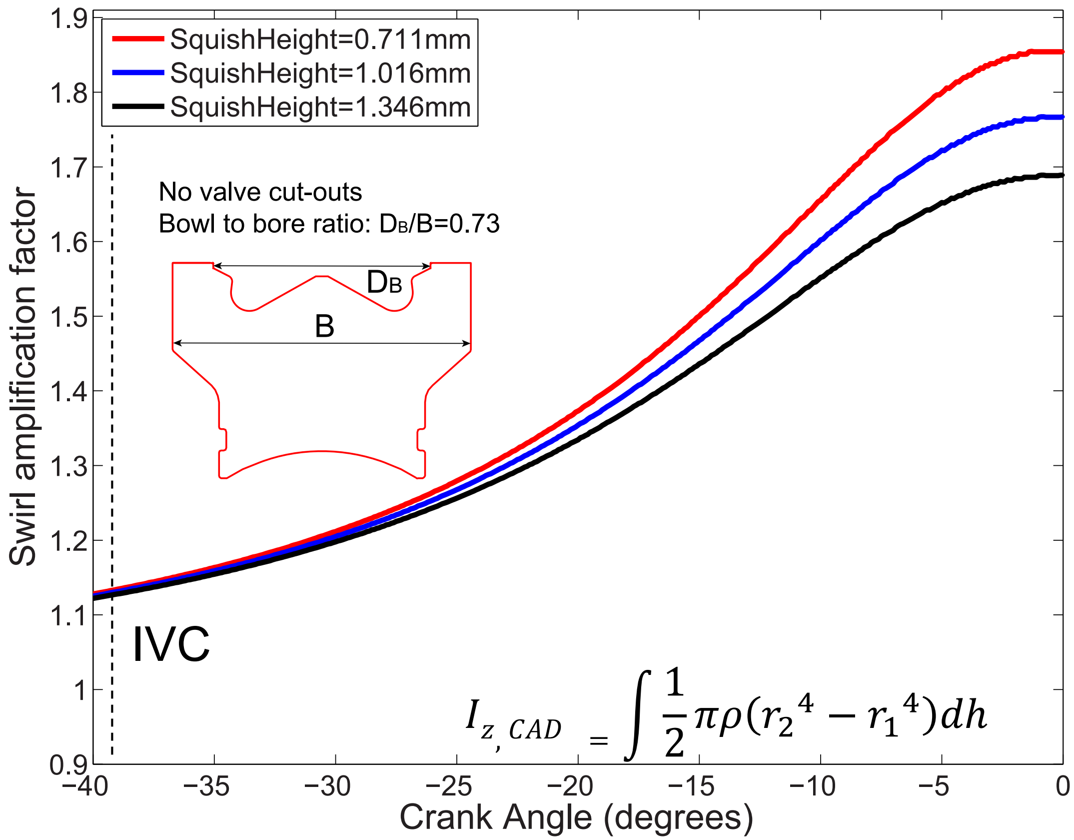
http://hyperphysics.phy-astr.gsu.edu/hbase/rstoo.html

Effect of Squish Height on Swirl Development

- Assuming solid body rotation along cylinder axis, swirl amplification effects can be quantified by a factor α_{CAD} which calculates how much the moment of inertia decreases from IVC.

$$\alpha_{CAD} = \frac{\omega_{CAD}}{\omega_{IVC}} = \frac{I_{z,IVC}}{I_{z,CAD}}$$

- Decreasing squish height results in:
  - smaller moment of inertia, $\alpha_{CAD} \Uparrow$
  - higher charge density, $\alpha_{CAD} \Downarrow$
- More pronounced swirl development with decreasing squish height suggests the change in moment of inertia dominates swirl development.



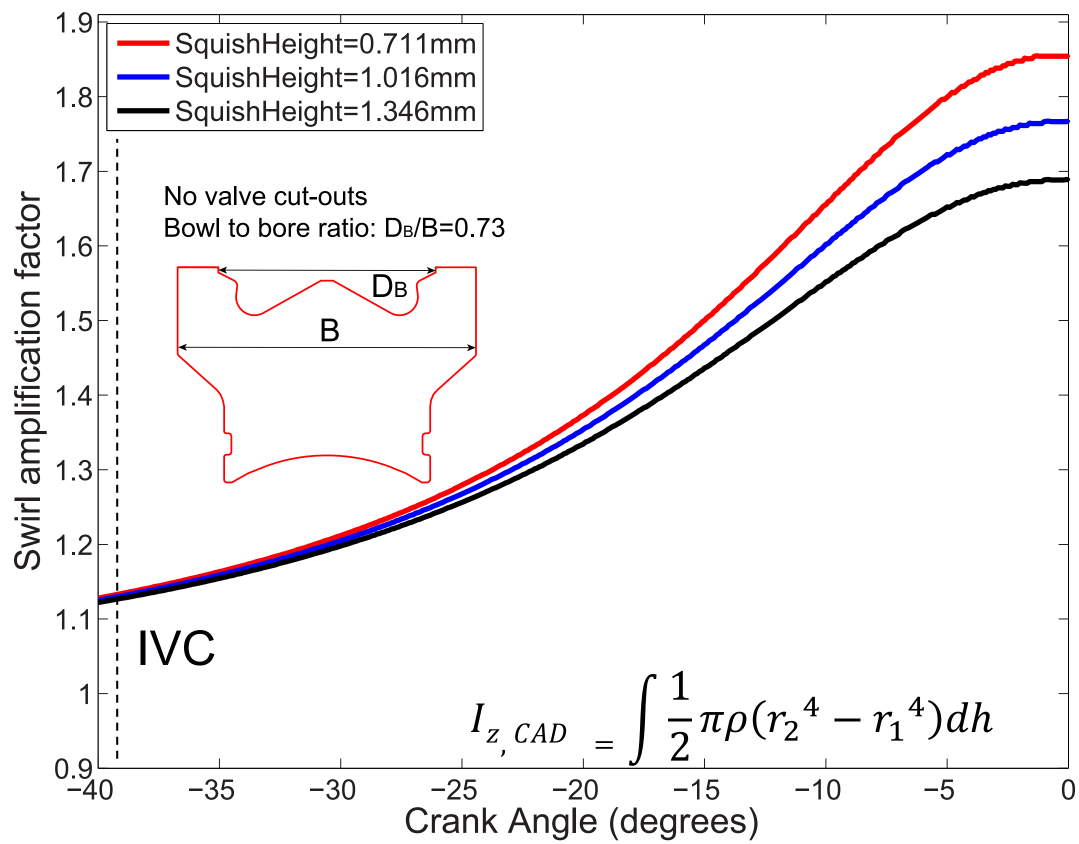
$$I_{z,CAD} = \int \frac{1}{2}\pi\rho({r_2}^4 - {r_1}^4)dh$$

Effect of Squish Height on Swirl Development

- Assuming solid body rotation along cylinder axis, swirl amplification effects can be quantified by a factor α_{CAD} which calculates how much the moment of inertia decreases from IVC.

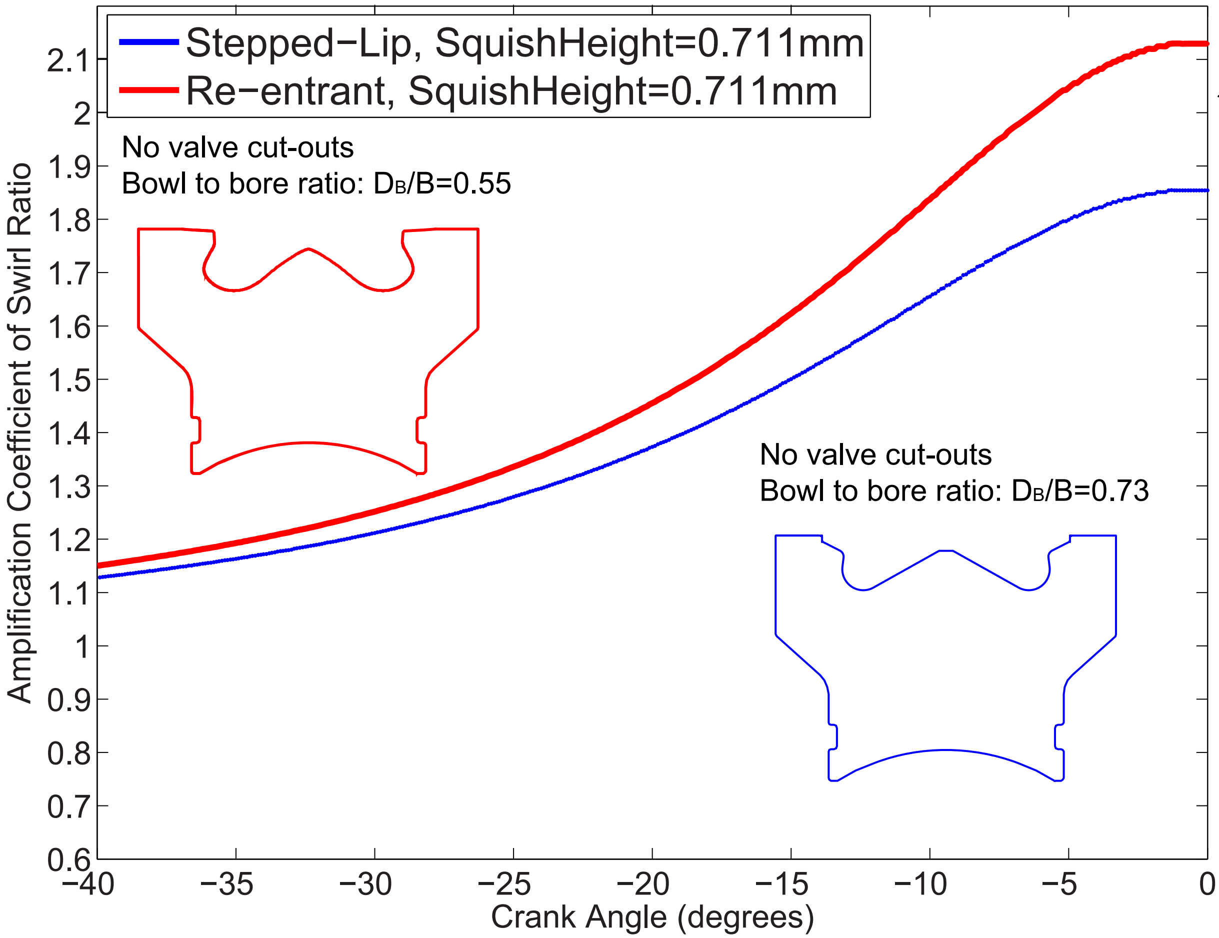
$$\alpha_{CAD} = \frac{\omega_{CAD}}{\omega_{IVC}} = \frac{I_{z,IVC}}{I_{z,CAD}}$$

- The effect of squish height in swirl development is more obvious near TDC.
- Draw backs to this simplified analysis
  - Assumption: solid body rotation around cylinder axis
  - Impact of valve cut-outs are neglected
  - Influence from intake flow is neglected

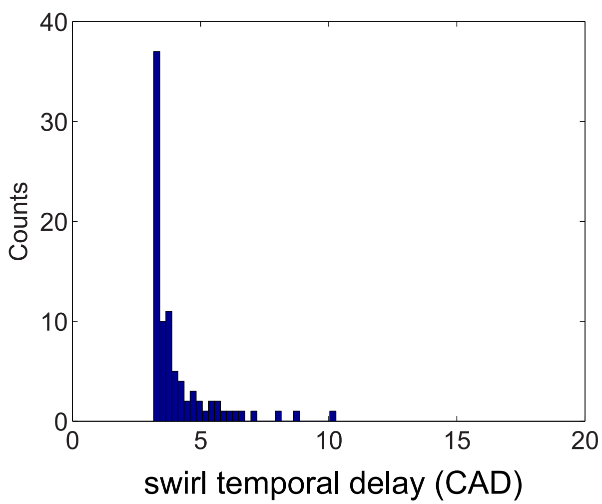


Effect of Piston Geometry in Swirl Development

- With the same squish height and compression ratio, swirl amplification is less pronounced with the stepped-lip piston bowl which results in a temporal delay by 4.4 CAD(σ=2.9 CAD) from late compression until TDC.
- The temporal delay of swirl development increases with piston compression.

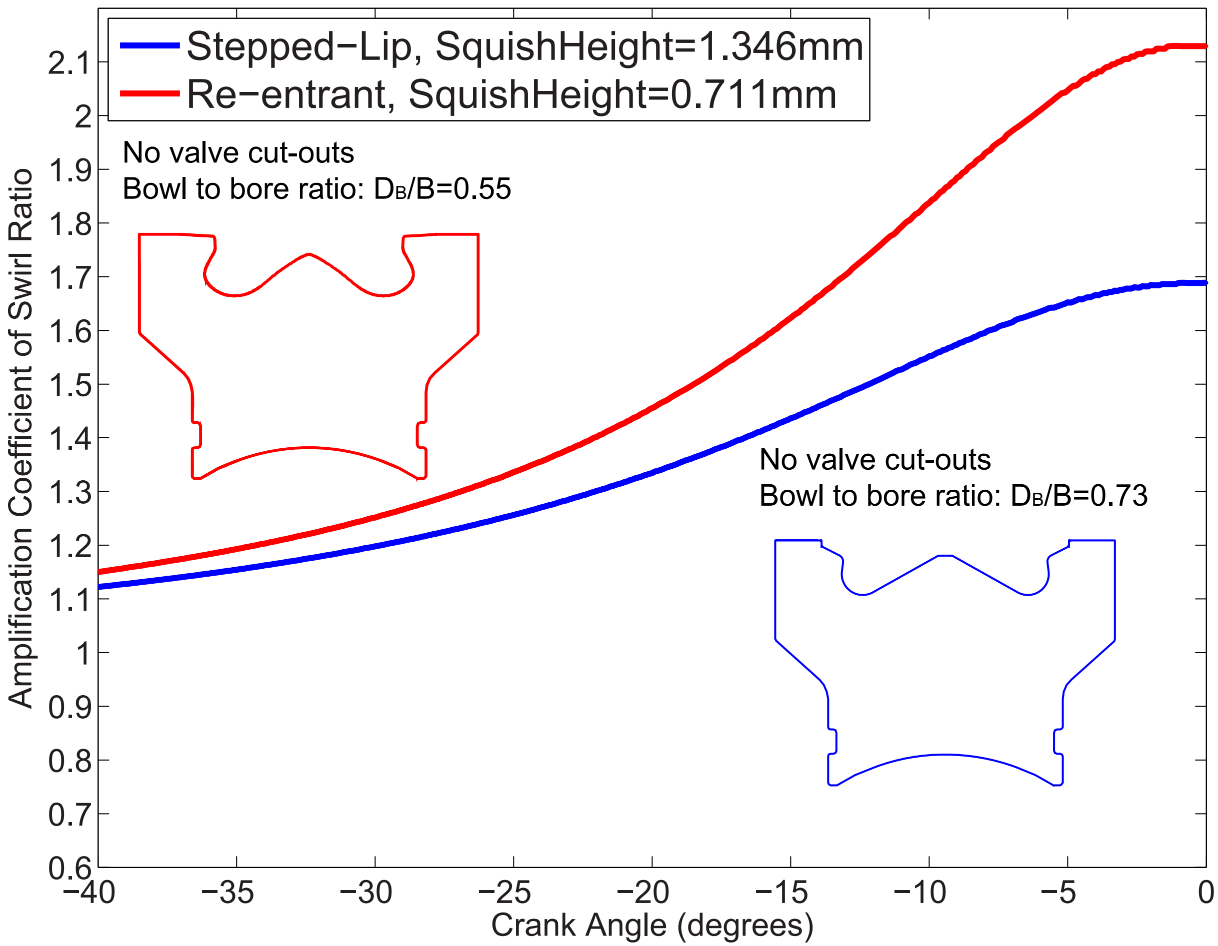


- Peak swirl amplification with stepped-lip geometry is 19.7% higher than that with the re-entrant geometry.

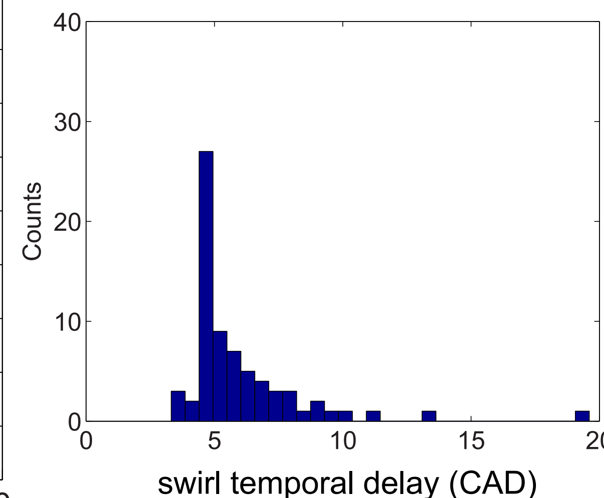


Effect of Piston Geometry in Swirl Development

- With a larger squish height, swirl amplification becomes even less pronounced with the stepped-lip piston bowl.
- The temporal delay of swirl amplification increase by 6.4 CAD (σ=4.4 CAD) until TDC.



- <u>This configuration mimics the current experimental setups.</u>



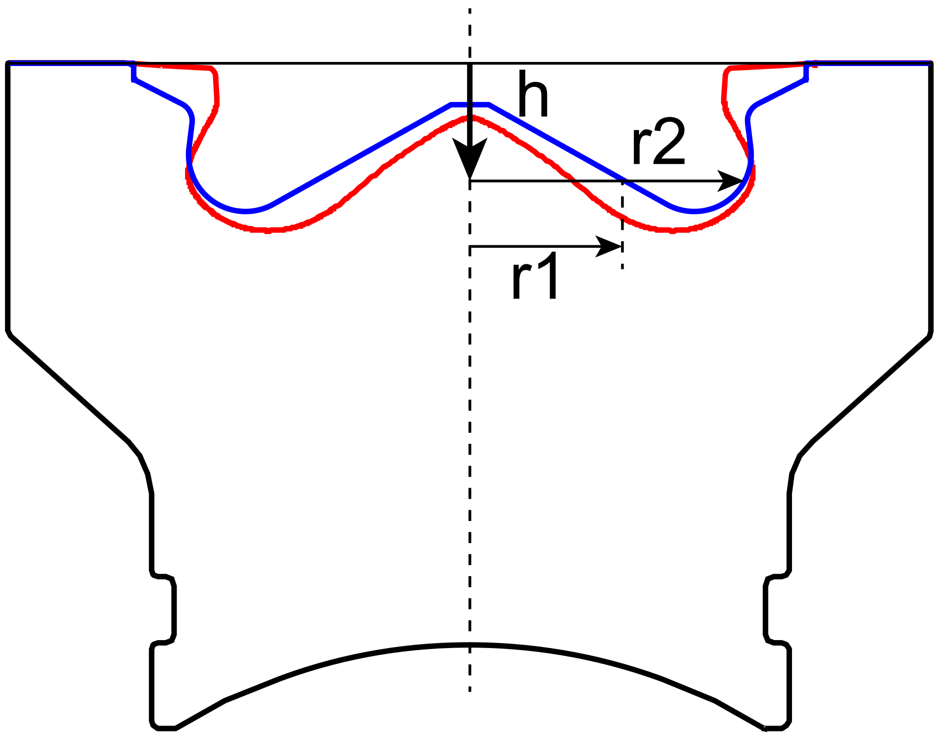
Effect of Piston Geometry in Swirl Development

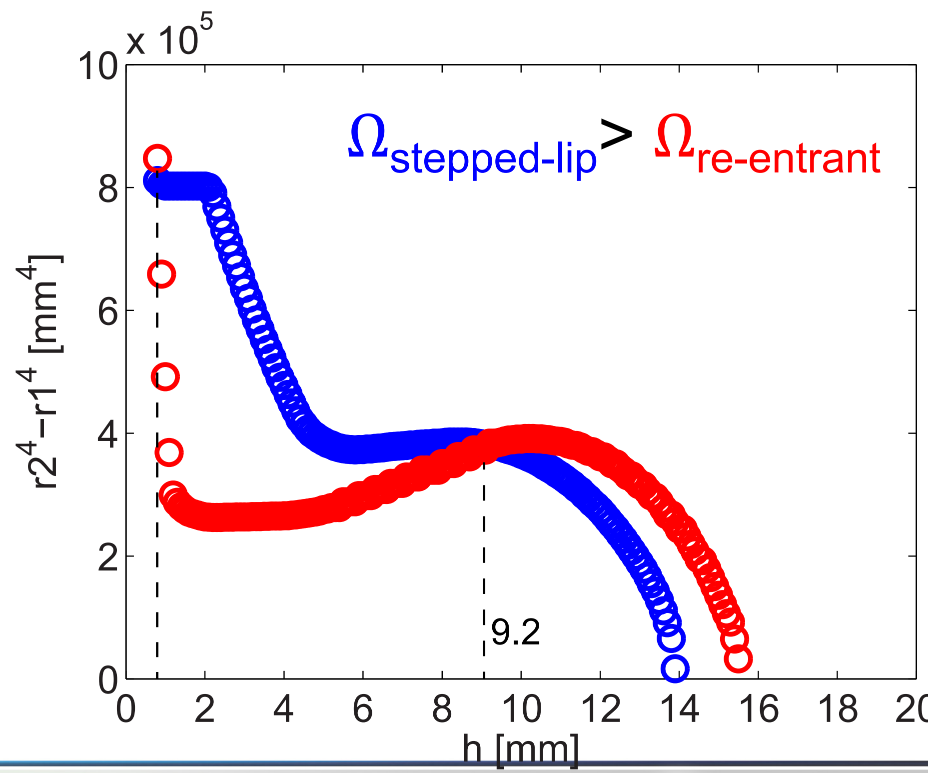
charge density

$$I_z = \frac{1}{2}\pi\rho \int (r_2{}^4 - r_1{}^4)\,dh$$

angular momentum — geometry

- For a given squish height and compression ratio, as the piston approaches TDC, the bowl geometry can substantially change the moment of inertia for the charge inside the bowl by changing the integral $\Omega = \int (r_2{}^4 - r_1{}^4)\,dh$.





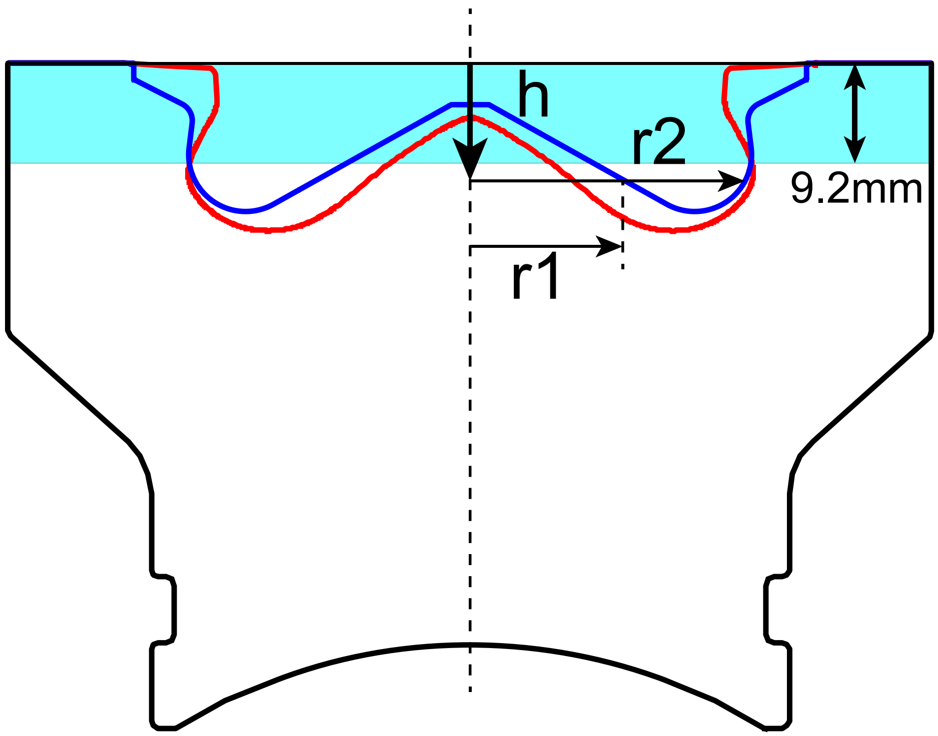
Effect of Piston Geometry in Swirl Development

charge density

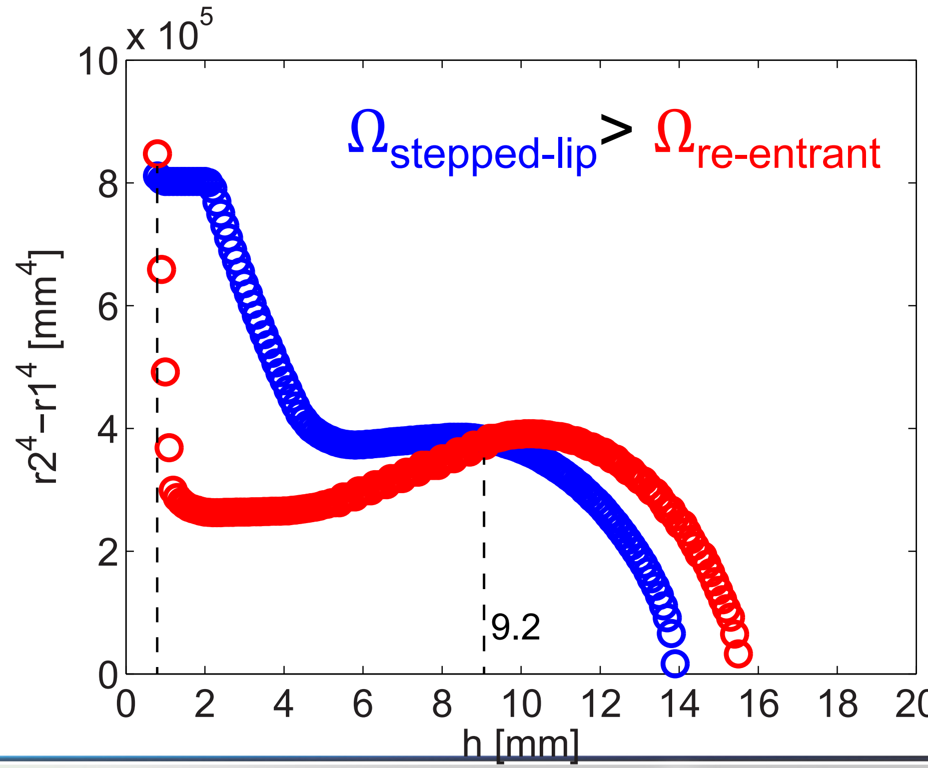
$$I_z = \frac{1}{2}\pi\rho \int (r_2{}^4 - r_1{}^4)dh$$

angular momentum

geometry



- Larger values of the integral $\Omega = \int (r_2{}^4 - r_1{}^4)dh$ means the swirl develops more slowly.
- The geometry difference in the upper portion of the stepped-lip piston bowl (in the blue region) is the main reason for its slower increase rate of swirl amplification factor α_{CAD} during compression stroke.

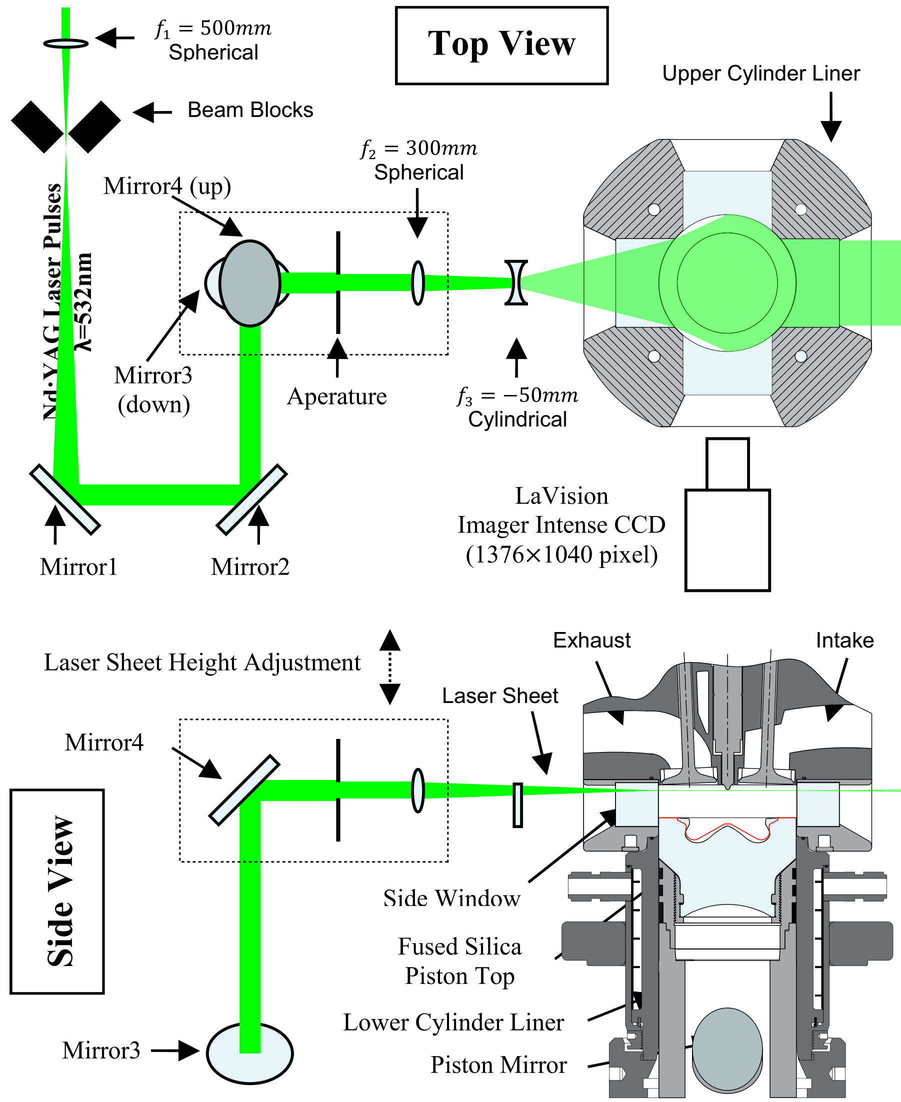


Swirl-Plane PIV Measurement Setup and Test Cases

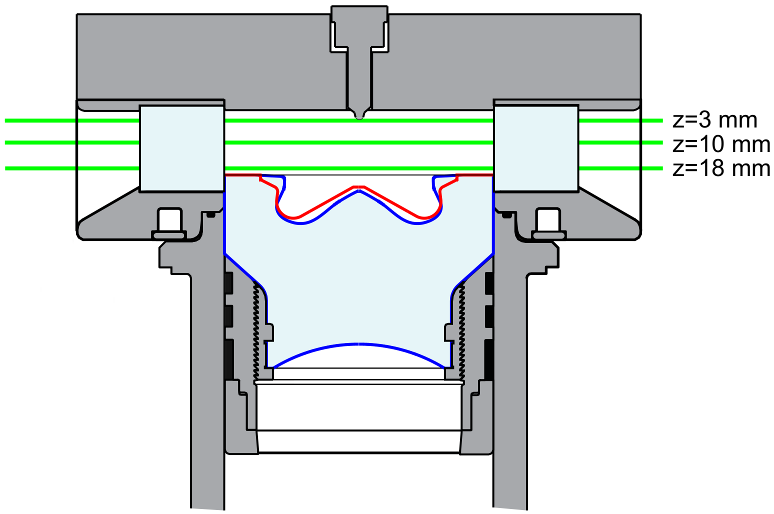
GM 1.9 L Diesel Engine	
Bore	82 mm
Stroke	90.4 mm
Displacement Volume	0.477 L
Geometric CR	16.7 (re-entrant) 15.8 (stepped-lip)
Squish Height	0.711 mm (re-entrant) 1.346 mm (stepped-lip)
Intake / Exhaust Valves	2 / 2
Steady-state swirl Ratio	1.5, 2.2, 3.5
Engine Speed	1500 rpm
Intake Pressure	1.5 bar
Intake Temperature	99^{0}C
O2 Mole Fraction	10%
Constant total mass flow rate	8.936 g/s
Operating Condition	Motored

Test cases:

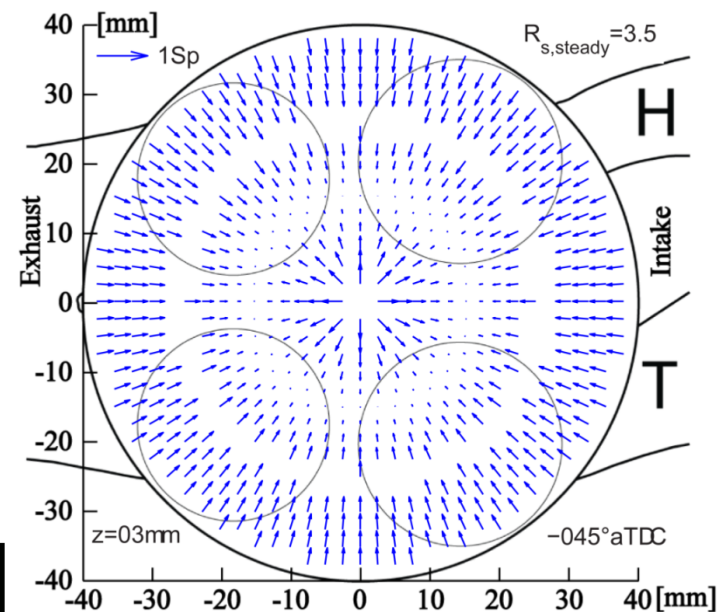
- Swirl-plane vertical position (below fire deck):
  - Half of squish height (within 20 CAD from firing TDC).
  - z=3mm, z=10mm and z=18mm for other crank angles.



Optical distortion correction is crucial to resolve accurate particle displacements for reliable velocity measurements.

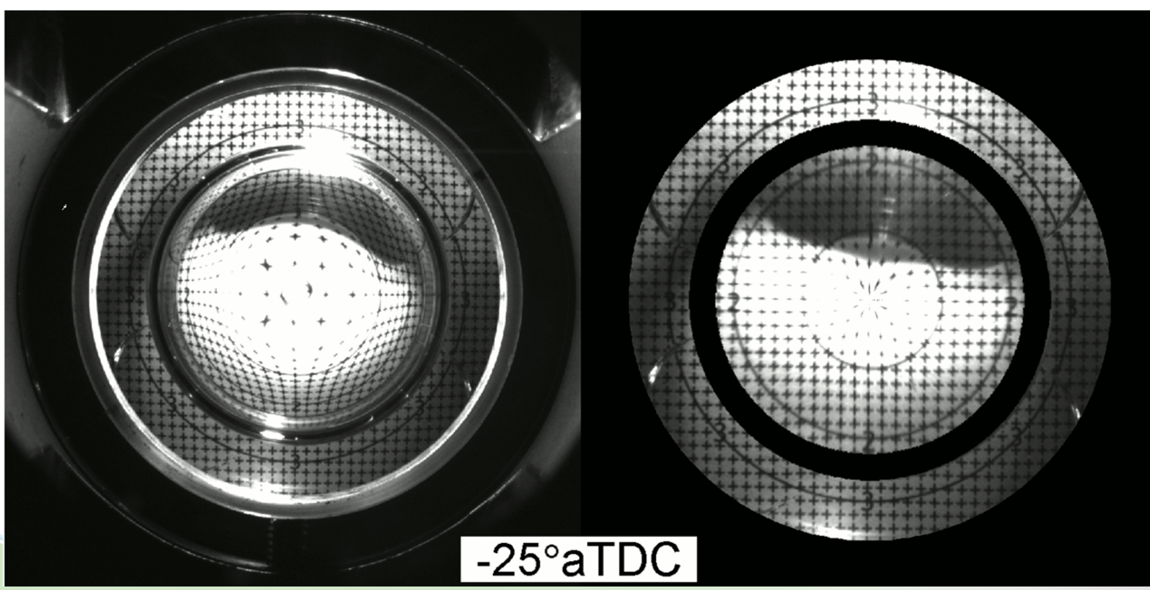


Artificial radial velocity @ -45°aTDC



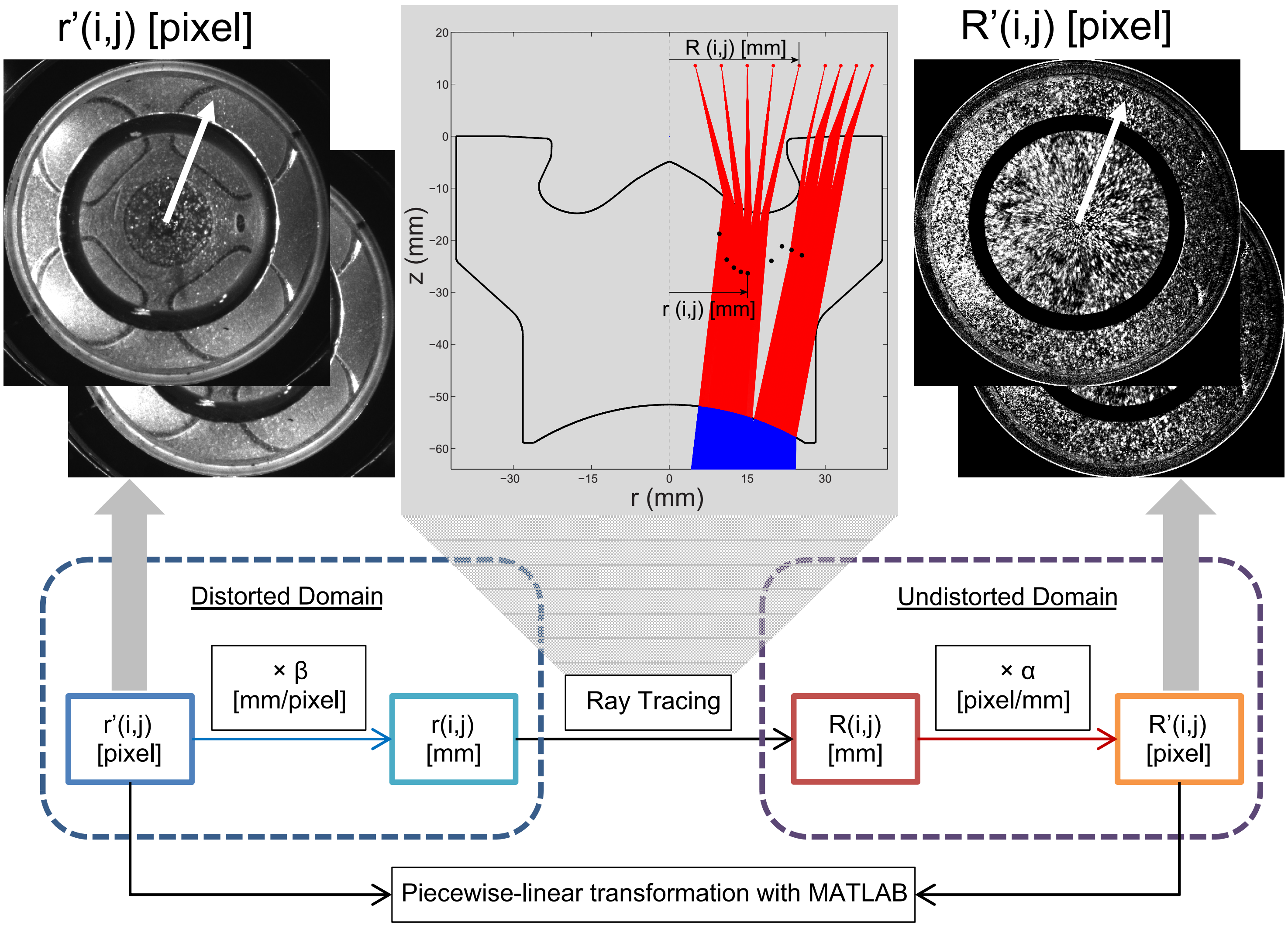
Raw Target Image

Dewarped Target Image



- Optical distortion induced by the piston is spatially and temporally dependent.
- Artificial radial velocity created by the incremental piston movement between two laser pulses is non-negligible.

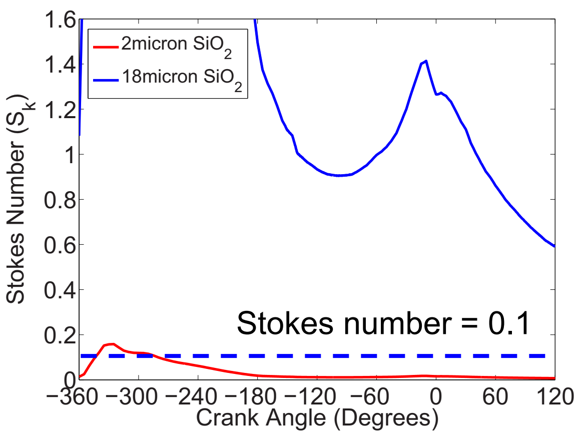
Ray tracing allows a full dewarping transformation with any given laser plane position and piston location.

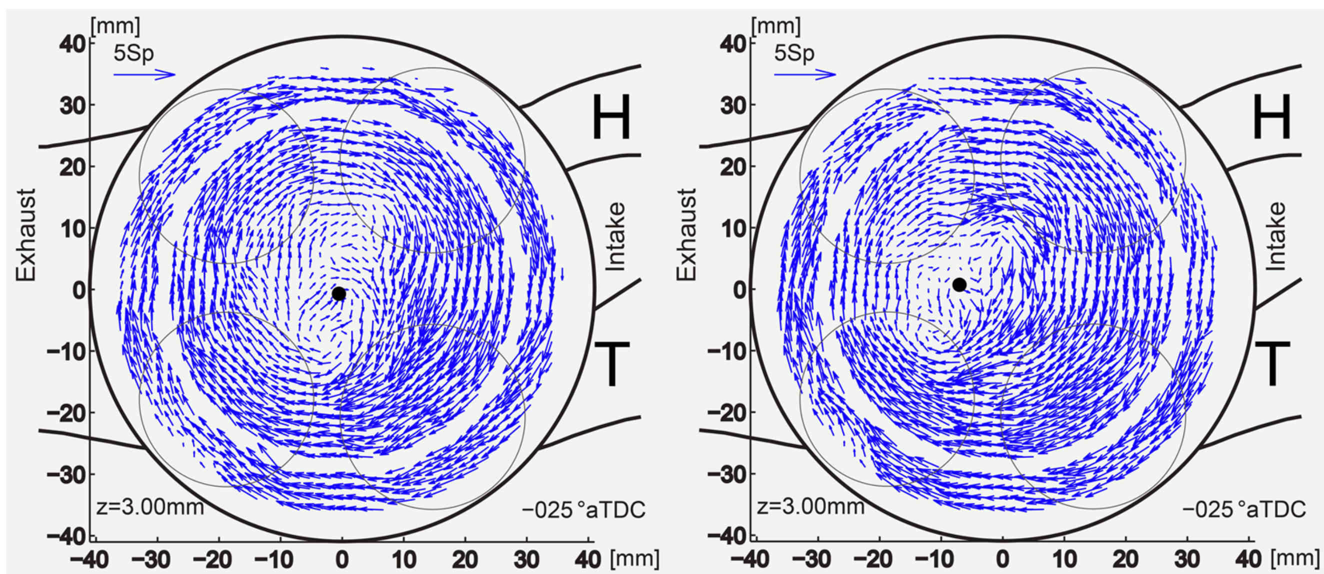


Zha, K., Busch, S., Miles, P. C., et. al. "Characterization of Flow Asymmetry During the Compression Stroke Using Swirl-Plane PIV in a Light-Duty Optical Diesel Engine with the Re-entrant Piston Bowl Geometry," *SAE Int. J. Engines* **8** (4), 2015, doi: 10.4271/2015-01-1699.

PIV Particle Fidelity Check

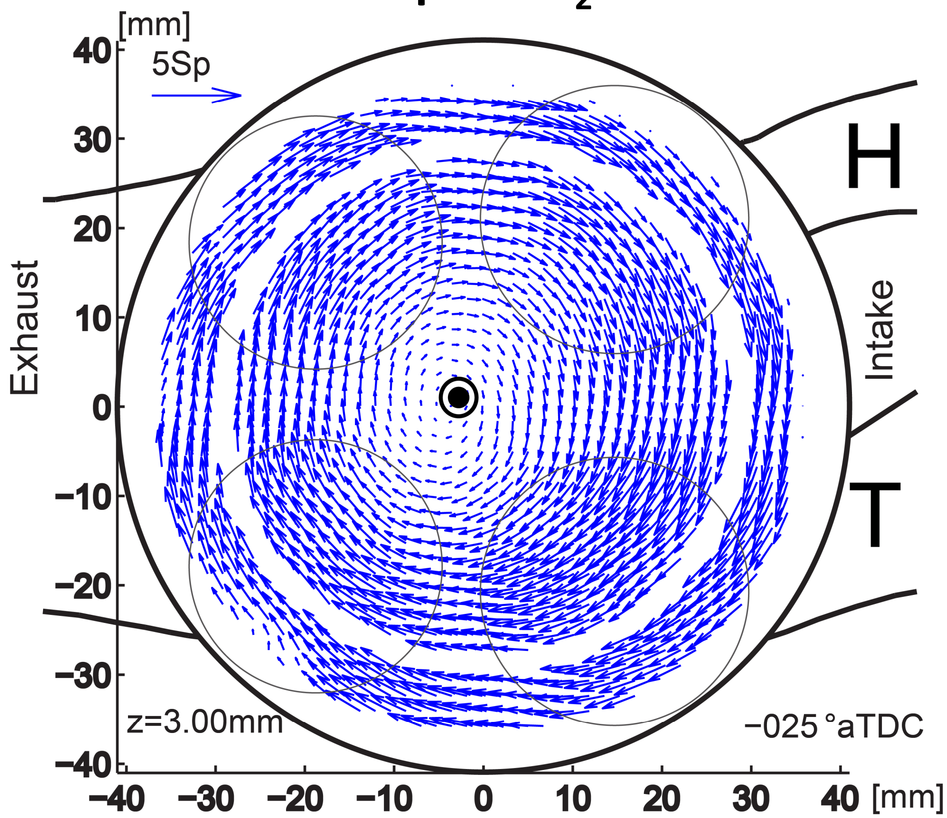
- Aerosol → size ~= 1 μm, Mie-scattering signal is too weak to image through the piston
- Lycopodium spores → size =32 μm, low ring friction, but induces large lag error
- Porous SiO_2
- 2 μm, small lag error, but creates ring friction problems
- 18 μm, lag error during early intake, and ring friction problems
- **2 μm Porous SiO_2** yields an acceptable flow tracing accuracy with errors < 1%.





Larger PIV tracer particles tend to bias the swirl center closer to chamber center due to their larger lag error.

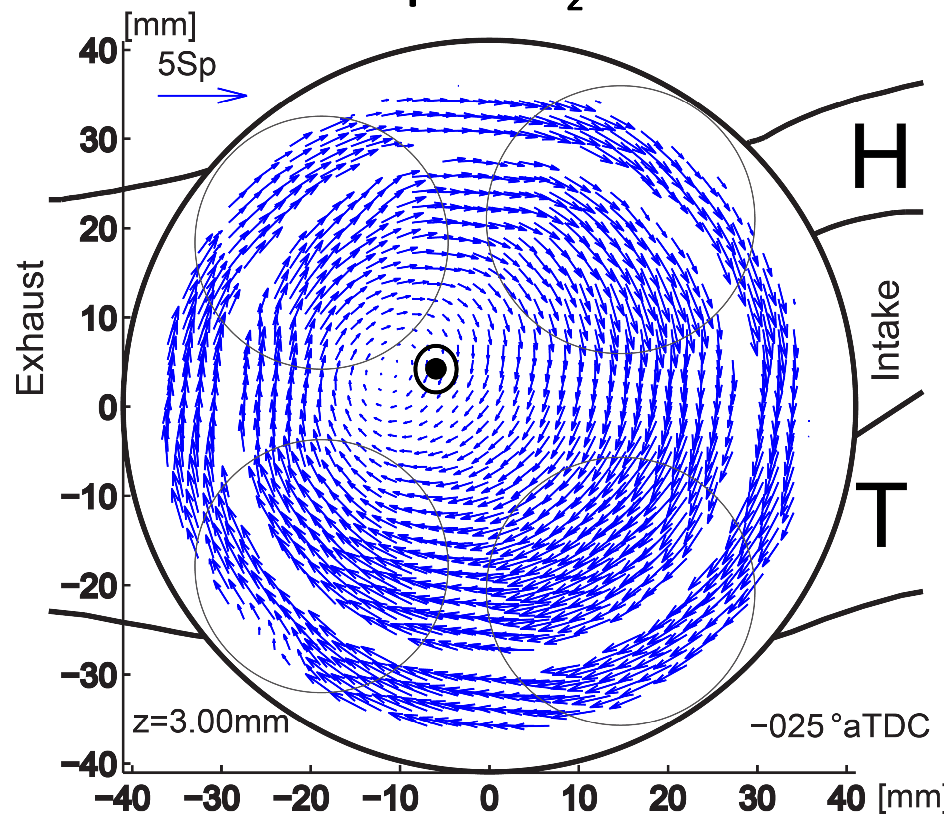
18µm SiO_2



- Mean swirl center location: [-2.7, 0.9] mm

  σ_x=2.0 mm, σ_y=2.1 mm

2µm SiO_2 ✓



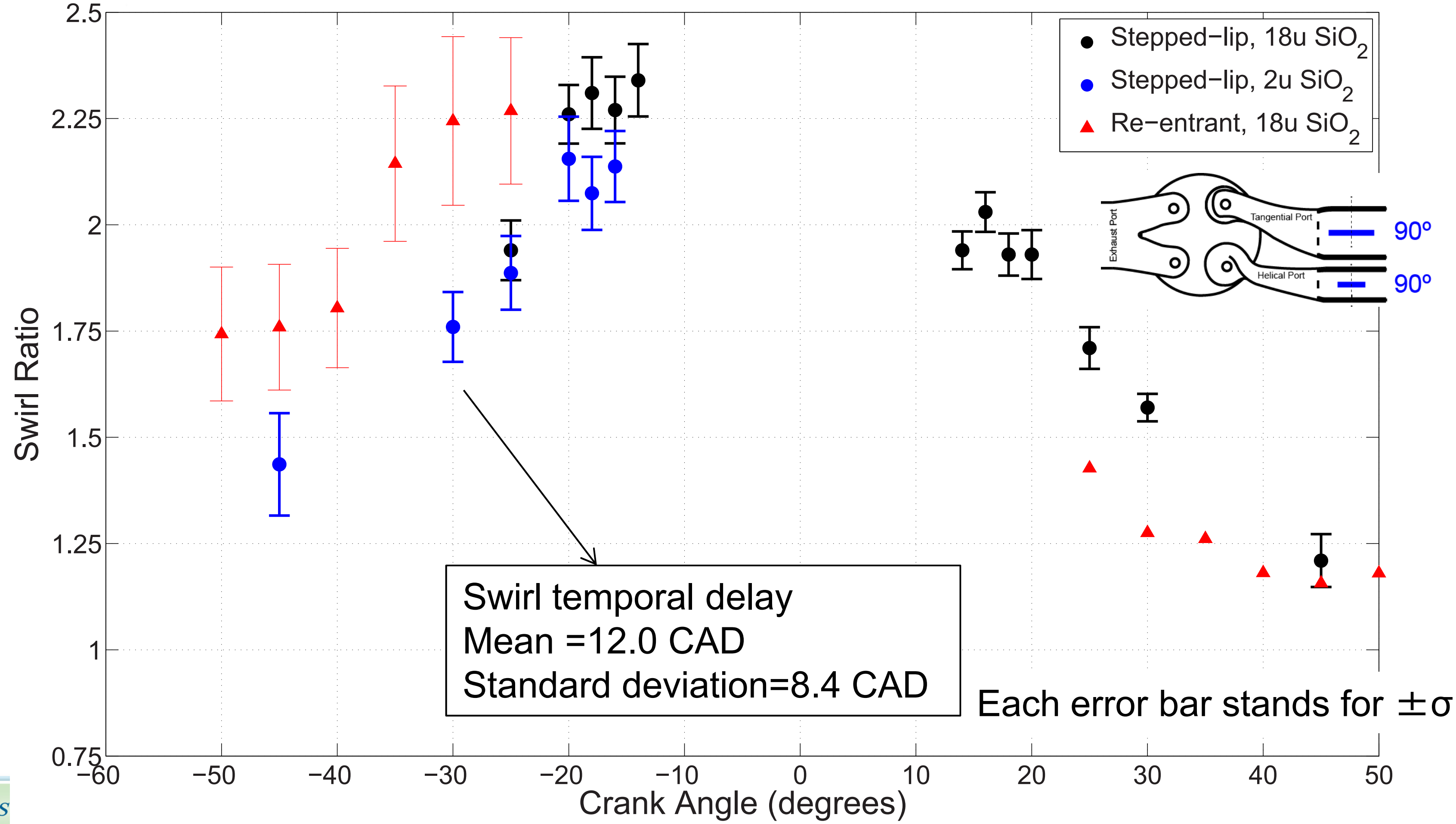
- Mean swirl center location: [-5.9, 4.1] mm

  σ_x=2.3 mm, σ_y=2.6 mm

Each black ellipse indicates one σ of swirl center location away from the mean positions.

During compression stroke until -25^{o}aTDC, swirl develops slower with stepped-lip piston geometry than with the re-entrant bowl geometry.

- The temporal delay of swirl development with the stepped-lip piston is statistically significantly larger than the delay given by the simplified analysis.
- Swirl temporal delay measured from PIV is statistically larger than that from 1-D simulation, which suggests intake flow & turbulence also have effects on swirl development.



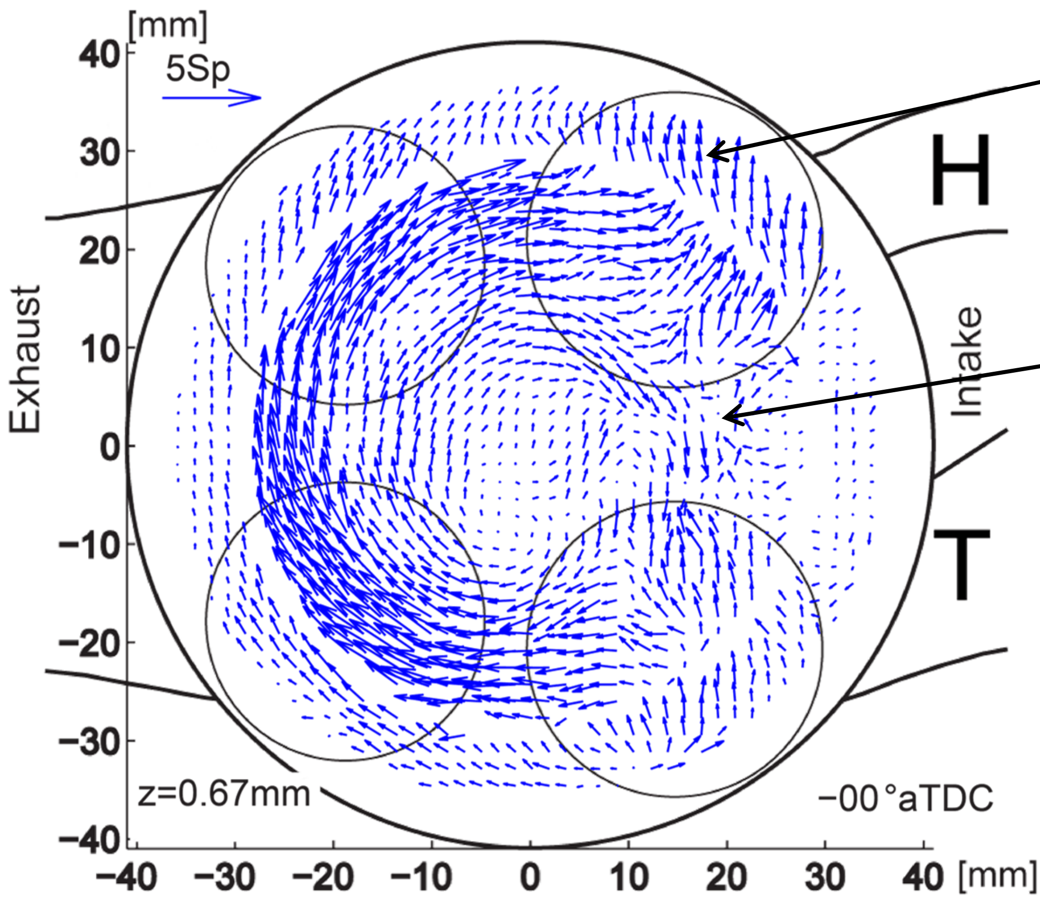
Besides background interference, beam steering effect prohibits reliable squish flow measurements.

18μm SiO_2, -0°aTDC, z=0.67mm

- Strong beam steering effects create streaks in the laser sheet; PIV processing is unsuccessful for squish flow measurements.

Besides background interference, beam steering effect and large dynamic range of velocities prohibit reliable squish flow measurements.

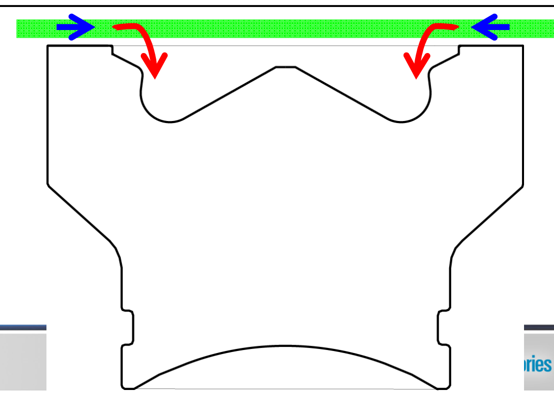
18µm SiO_2, -0°aTDC, z=0.67mm



Severe beam steering in the squish zone results in low correlation values and unreliable ensemble averaged data.

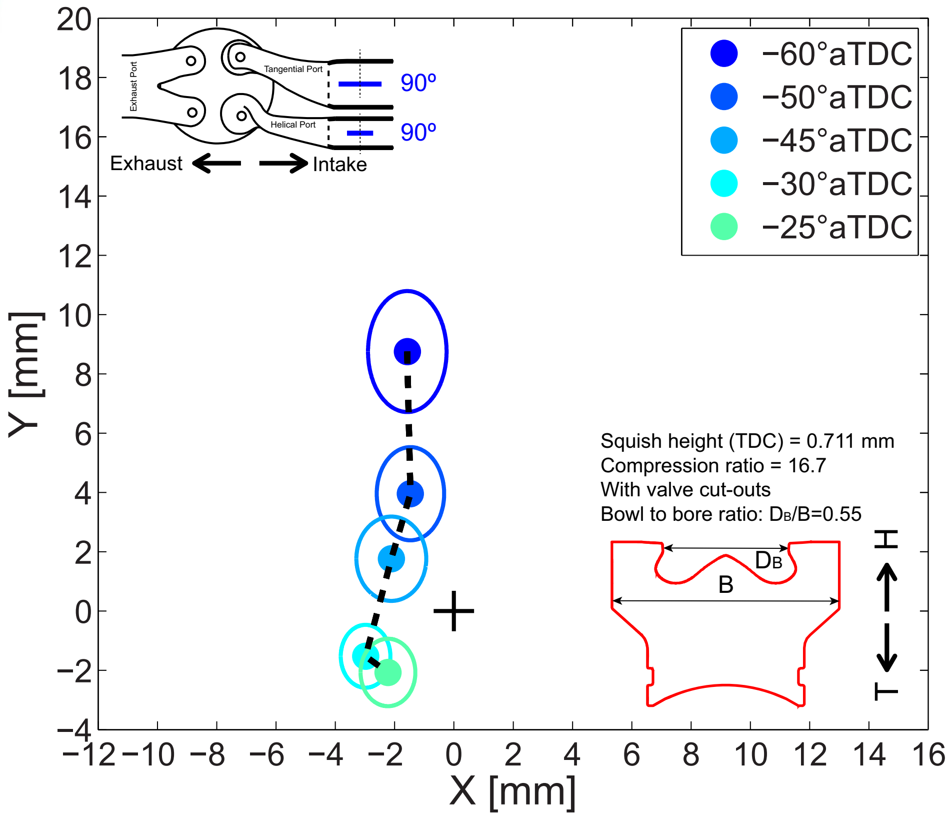
Background interference is stronger on intake valve side (slightly smaller squish height).

Capturing both slow flow in the squish region and fast out-of-plane velocity in the bowl region is difficult.

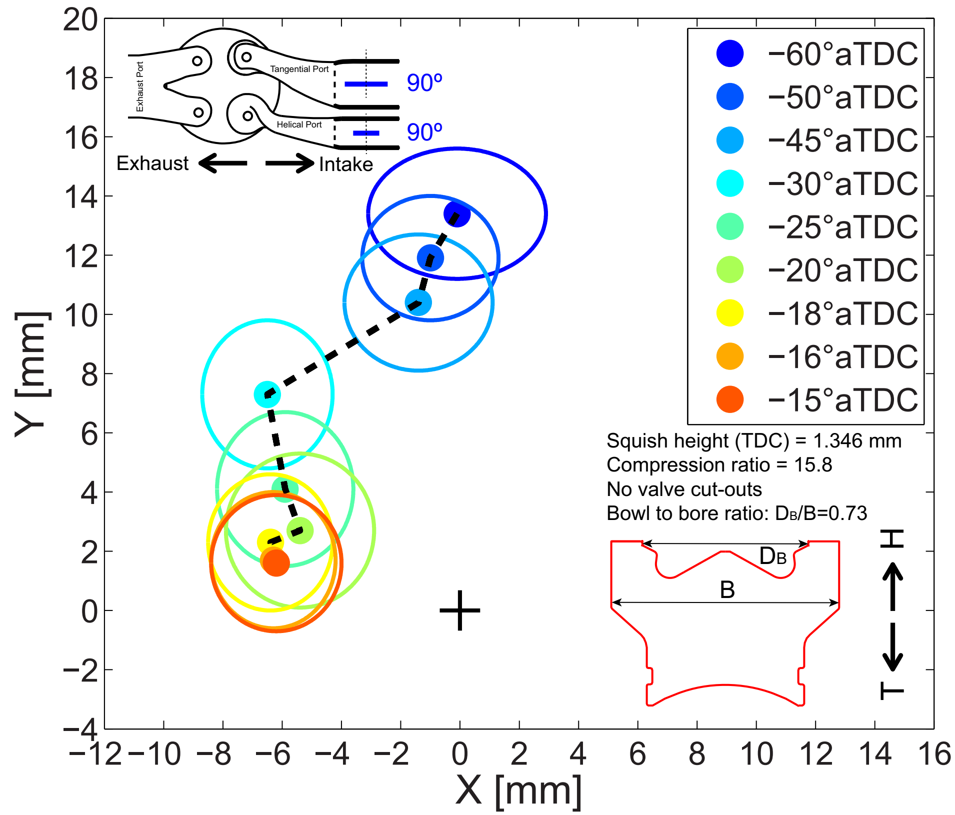


In-cylinder swirl with stepped-lip piston is more eccentric.

Re-entrant piston bowl, $R_{s,steady}$=2.2



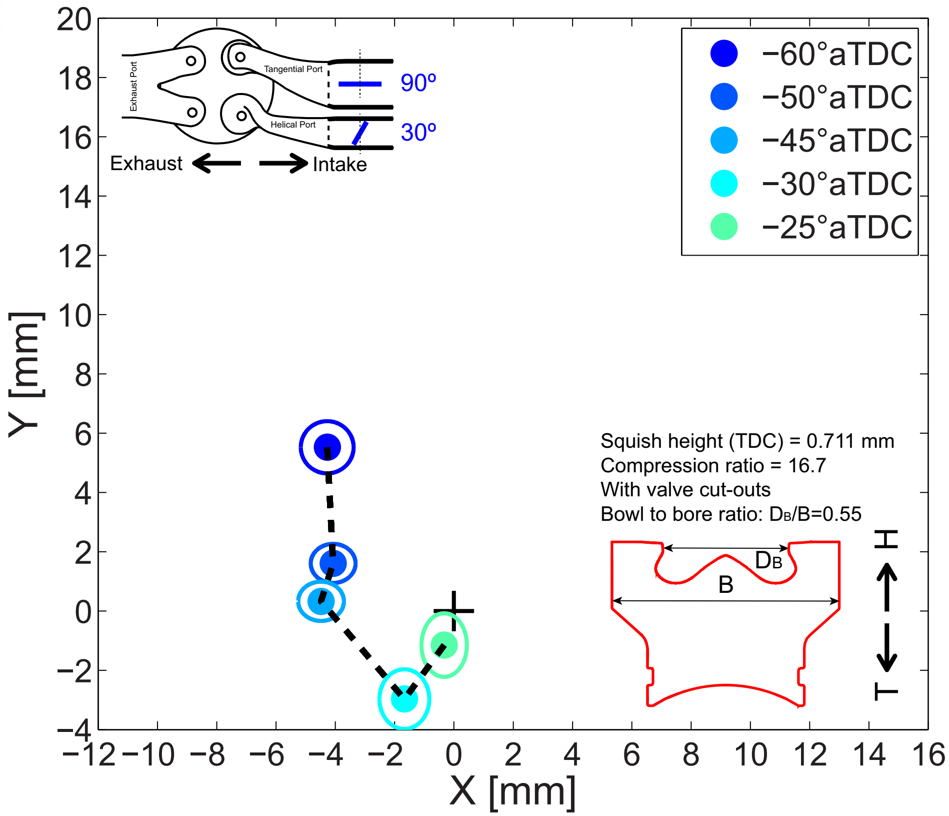
Stepped-lip piston bowl, $R_{s,steady}$=2.2



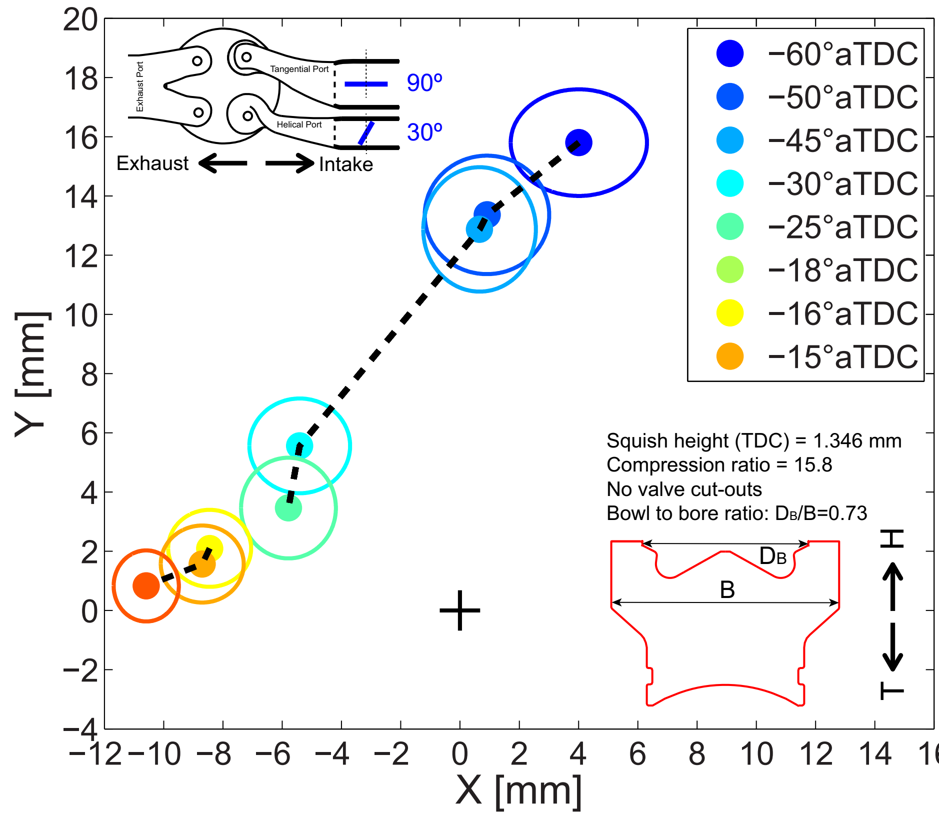
Each black ellipse indicates one σ of swirl center location away from the mean positions (out of 220 instantaneous velocity fields).

Swirl center motion changes as swirl ratio increases; cyclic variability (indicated by σ of swirl center location) is larger for the stepped-lip piston geometry.

Re-entrant piston bowl, $R_{s,steady}$=3.5



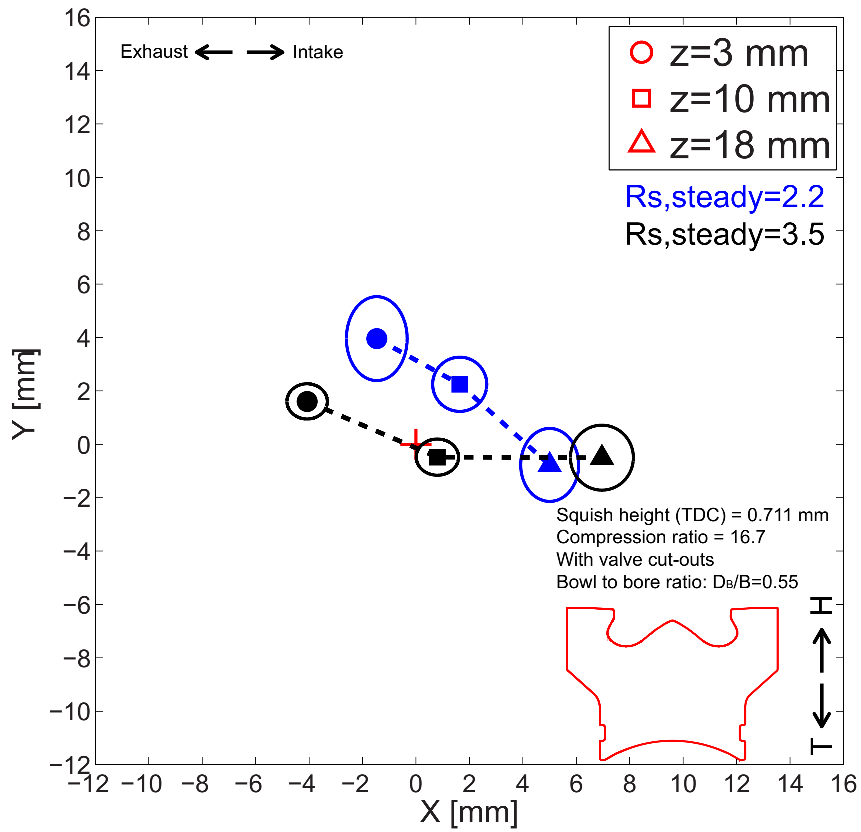
Stepped-lip piston bowl, $R_{s,steady}$=3.5



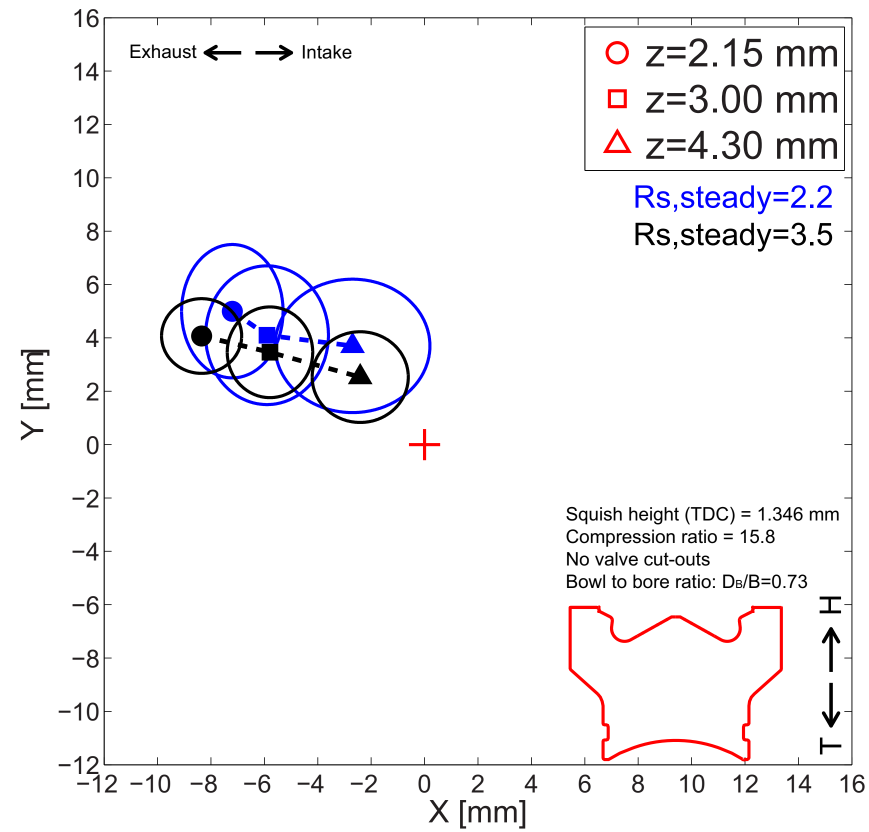
Each black ellipse indicates one σ of swirl center location away from the mean positions (out of 220 instantaneous velocity fields).

Piston geometry effect becomes dominant for swirl asymmetry in the late compression stroke.

Re-entrant piston bowl, CAD=-50^{0}aTDC



Stepped-lip piston bowl, CAD=-25^{0}aTDC



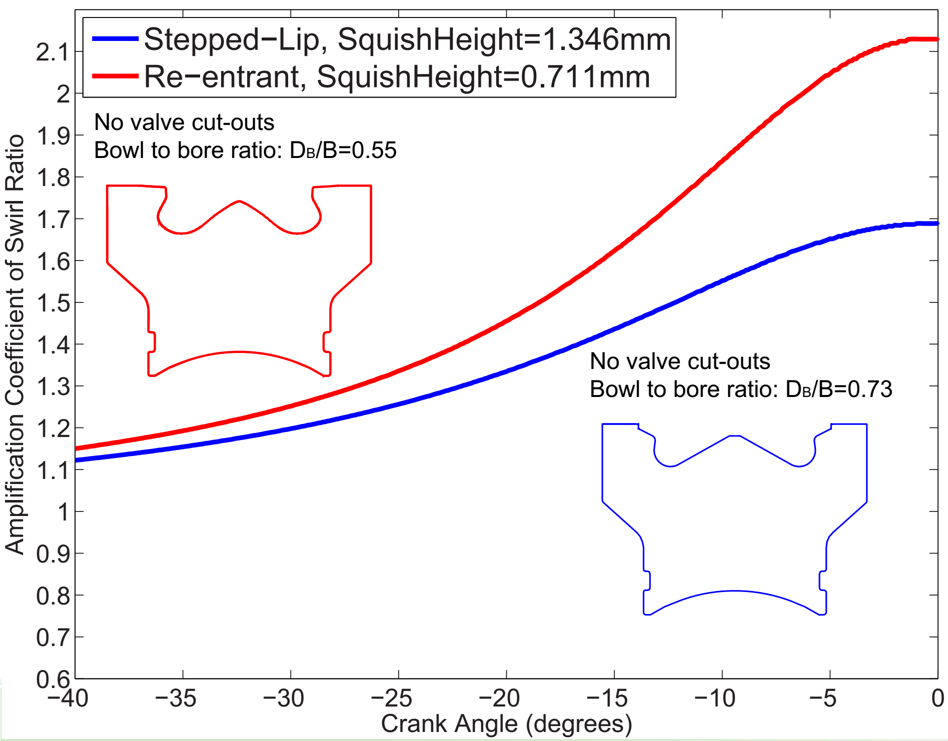
Each ellipse indicates one σ of swirl center location away from the mean positions (out of 220 instantaneous velocity fields).

Summary/Conclusions

- 1-D simulation based on angular momentum conservation demonstrates the swirl amplification mechanism with bowl-in-piston geometry.
- Both simulation (1-D) and experiments show that swirl development with stepped-lip piston geometry is less pronounced than that with re-entrant piston geometry in the late compression stroke until TDC.
- Swirl temporal delay measured from PIV is statistically larger than that from 1-D simulation, which suggests intake flow & turbulence also have effects on swirl development.

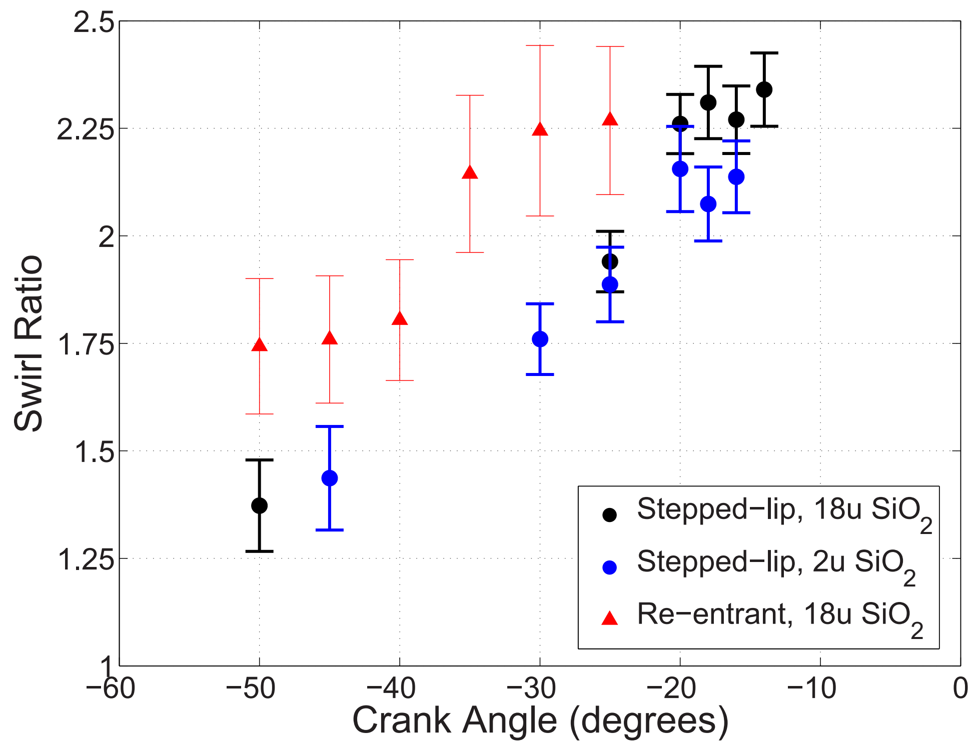
1-D Simulation

Swirl temporal delay μ=6.4 CAD, σ=4.4 CAD



Experimental Results from PIV

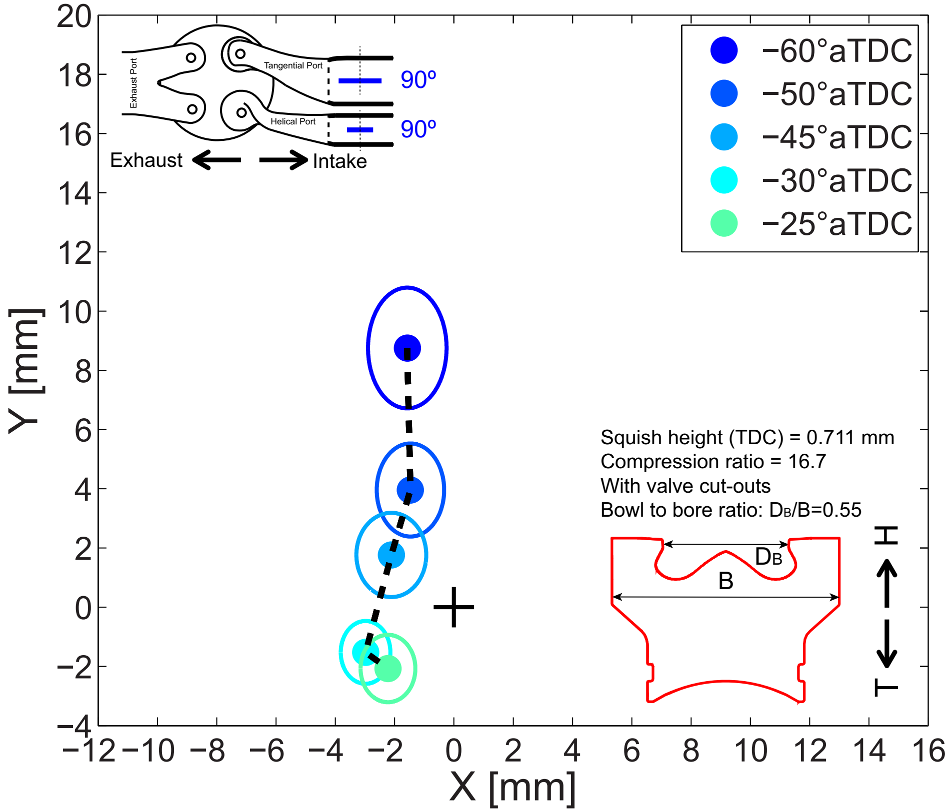
Swirl temporal delay μ=12.0 CAD, σ=8.4 CAD



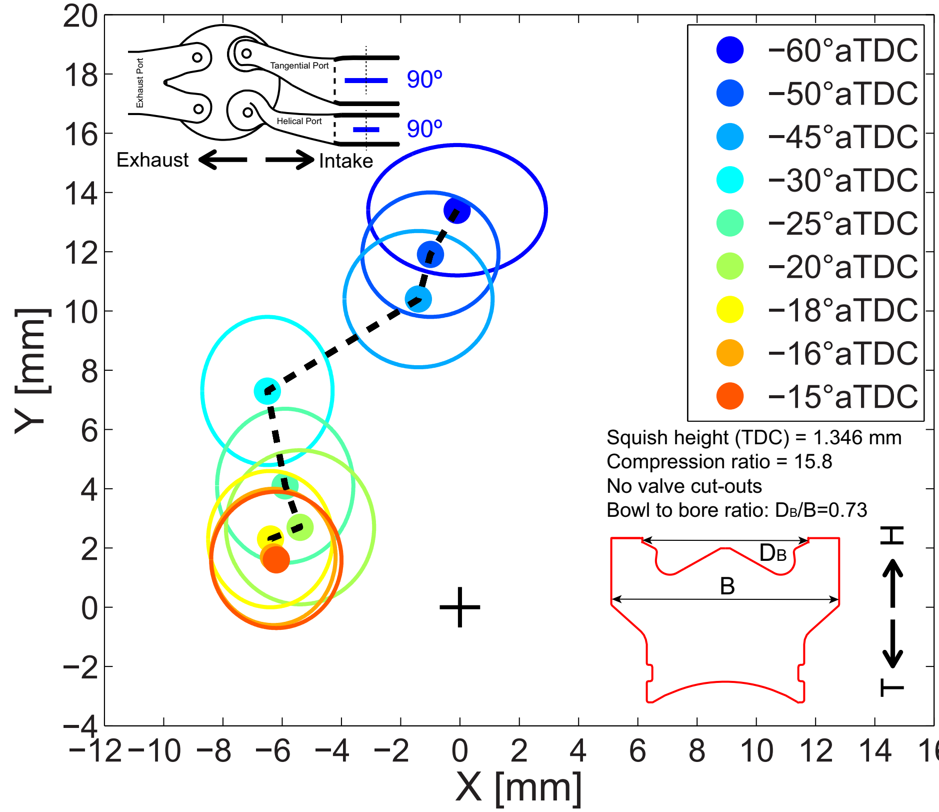
Summary/Conclusions

- In the late compression stroke, in-cylinder swirl is more eccentric and cyclic variability of swirl center location (indicated by σ of swirl center locations) is greater with the stepped-lip piston. This is the joint effect of piston geometry change and increased squish height.

Re-entrant piston bowl, $R_{s,steady}$=2.2



Stepped-lip piston bowl, $R_{s,steady}$=2.2

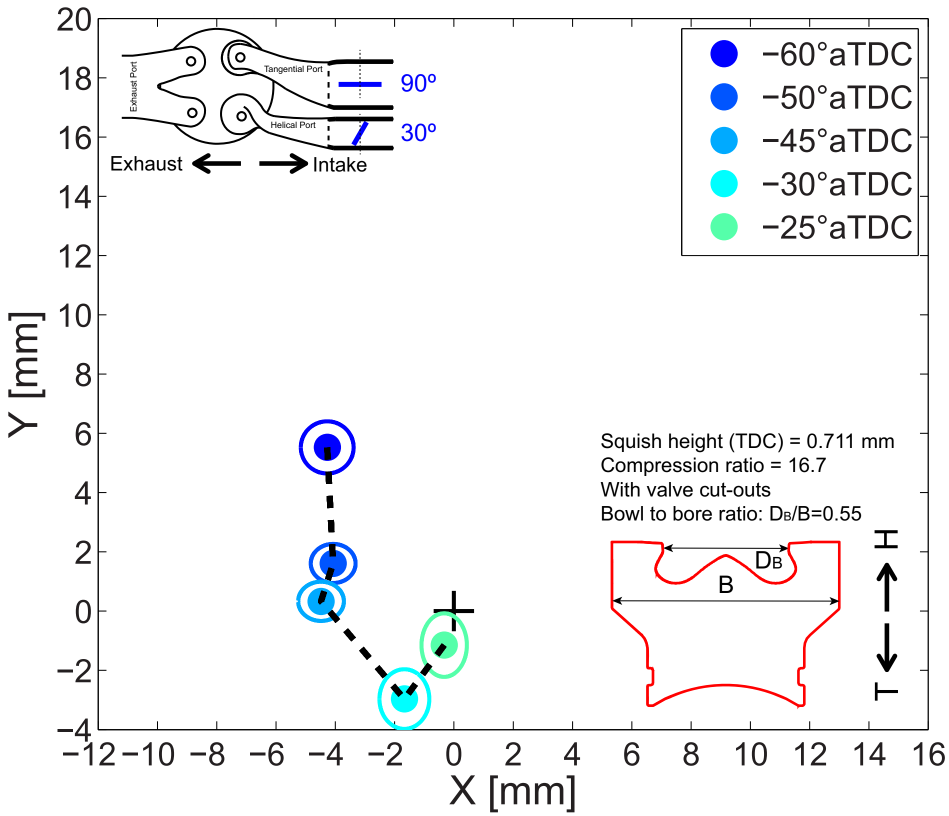


Each black ellipse indicates one σ of swirl center location away from the mean positions.

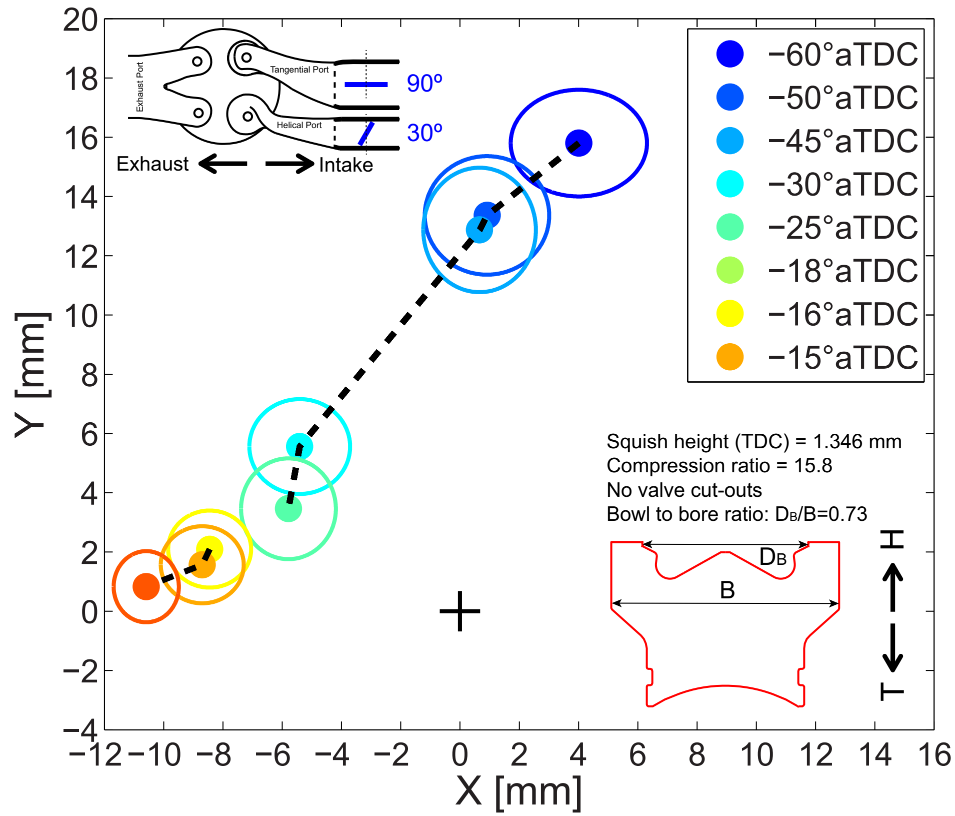
Summary/Conclusions

- In the late compression stroke, in-cylinder swirl is more eccentric and cyclic variability of swirl center location (indicated by σ of swirl center locations) is greater with the stepped-lip piston. This is the joint effect of piston geometry change and increased squish height.

Re-entrant piston bowl, $R_{s,steady}$=3.5



Stepped-lip piston bowl, $R_{s,steady}$=3.5

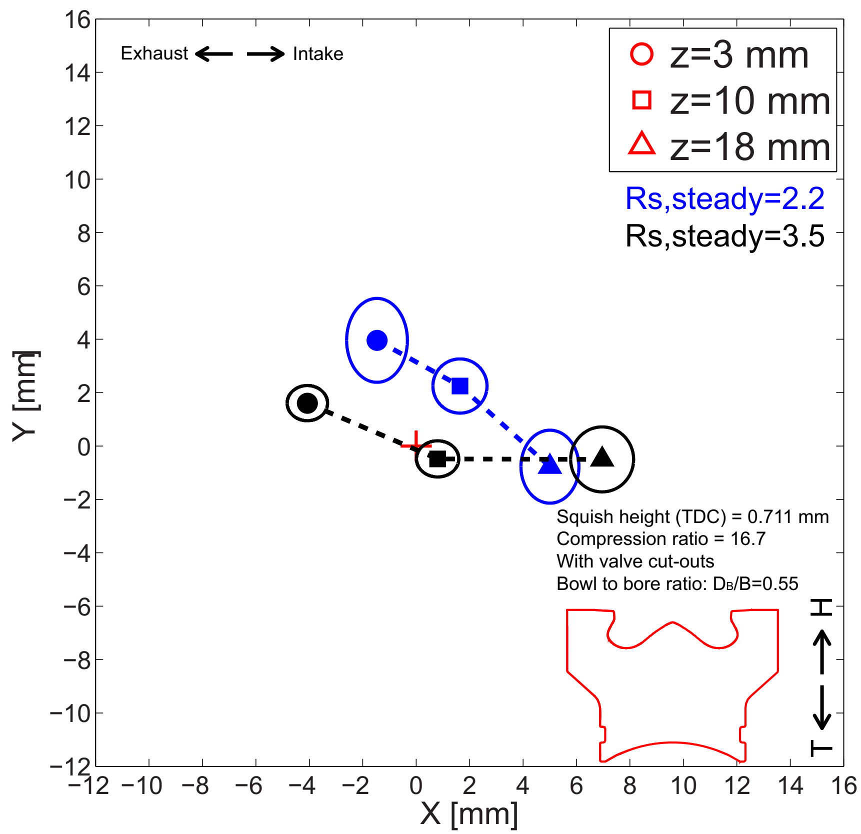


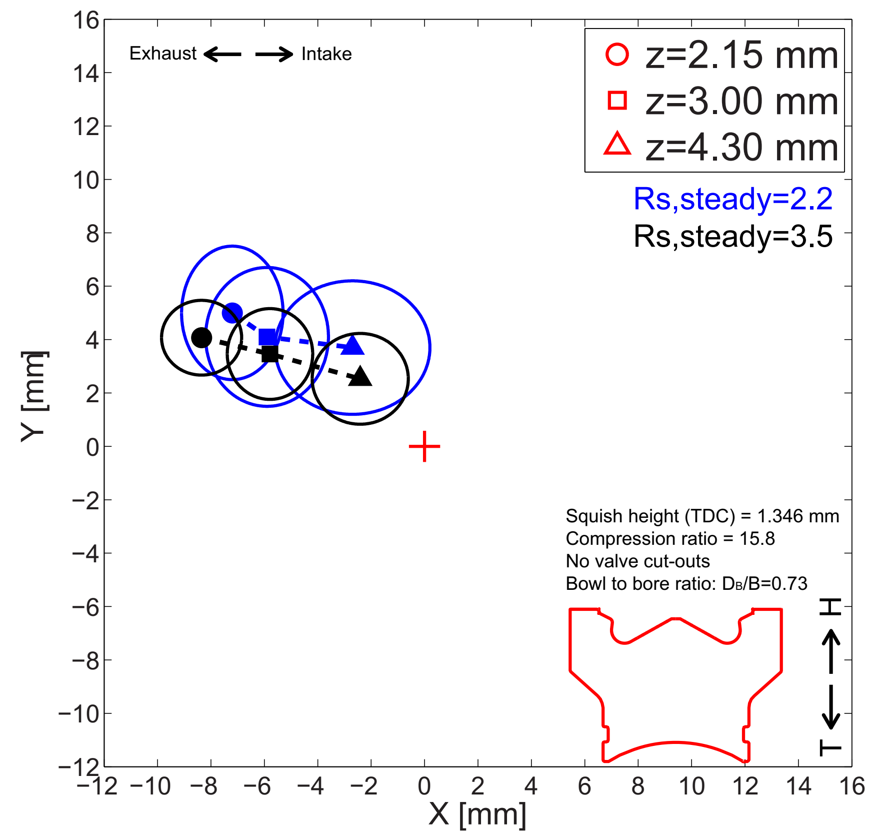
Each black ellipse indicates one σ of swirl center location away from the mean positions.

Summary/Conclusions

- Piston geometry effect becomes dominant in the late compression stroke: the swirl center location is closer to the intake valve in lower planes.

Re-entrant piston bowl, CAD=-50⁰aTDC **Stepped-lip piston bowl, CAD=-25⁰aTDC**





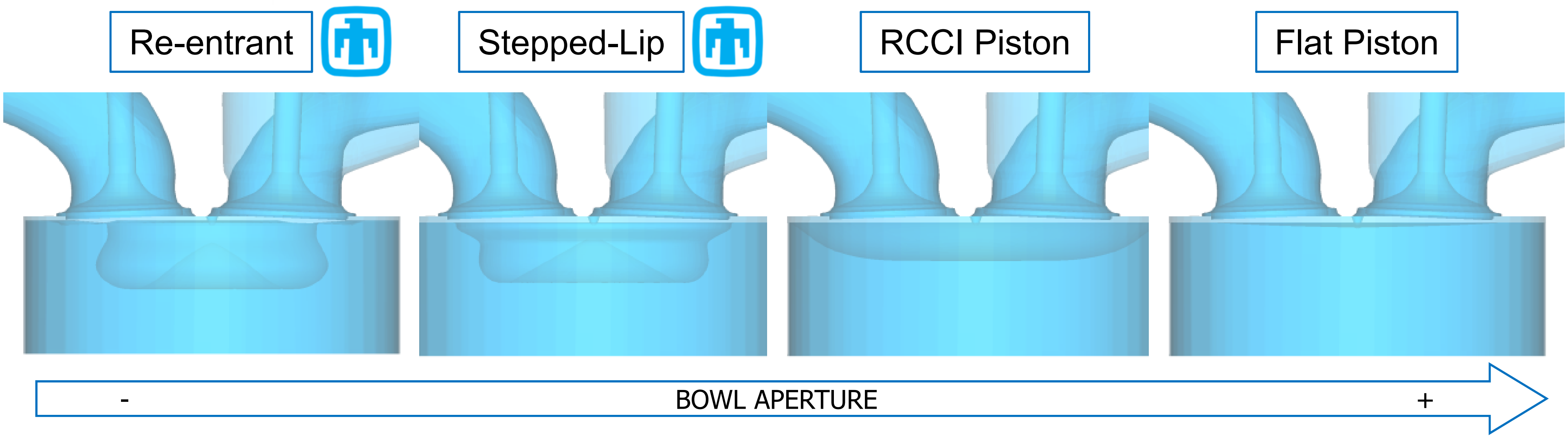
Each ellipse indicates one σ of swirl center location away from the mean positions (out of 220 instantaneous velocity fields).

Future Work: compare with results from simulation

University of Wisconsin -- Engine Research Center

- Bowl shape effects on swirl structure and local turbulence availability in the SNL light-duty engine

by **FRESCO**

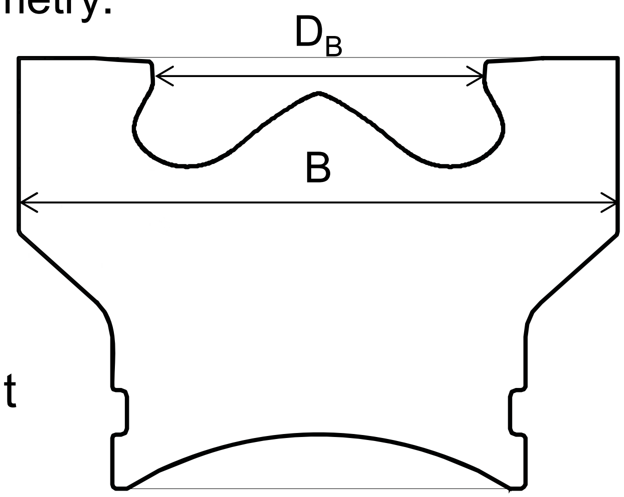


1) Squish height affects amount of squish flow → Keep constant squish height instead of compression ratio
2) Analyze effects of squish height on flow structure

Future Work

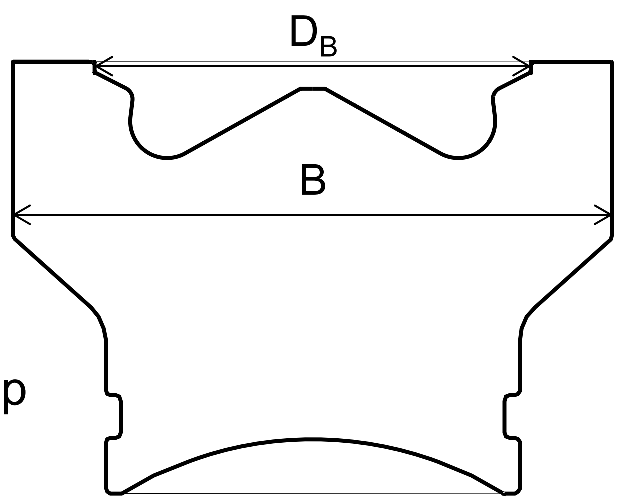
- Further investigation is needed to isolate effect of squish height away from piston geometry.

Re-entrant



- Squish height (TDC) = 0.711 mm
- Compression ratio = 16.7
- With valve cut-outs
- Bowl to bore ratio: D_B/B=0.55

Stepped-lip



- Squish height (TDC) = 1.346 mm
- Compression ratio = 15.8
- Different optical distortion pattern
- No valve cut-outs
- Bowl to bore ratio: D_B/B=0.73

Future Work

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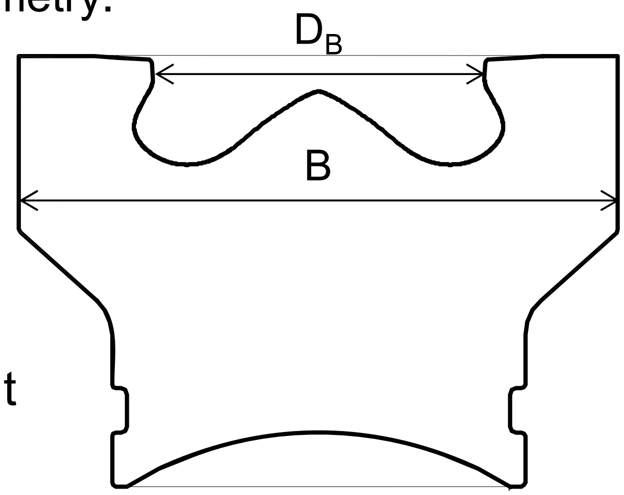
Re-entrant



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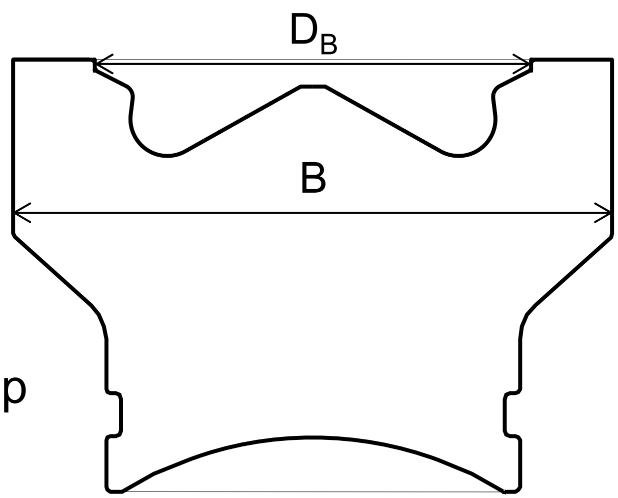

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THANK YOU FOR YOUR ATTENTION !
QUESTIONS?