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PISTON GEOMETRY EFFECTS ON IN-CYLINDER SWIRL ASYMMETRY IN A LIGHT-DUTY OPTICAL DIESEL ENGINE

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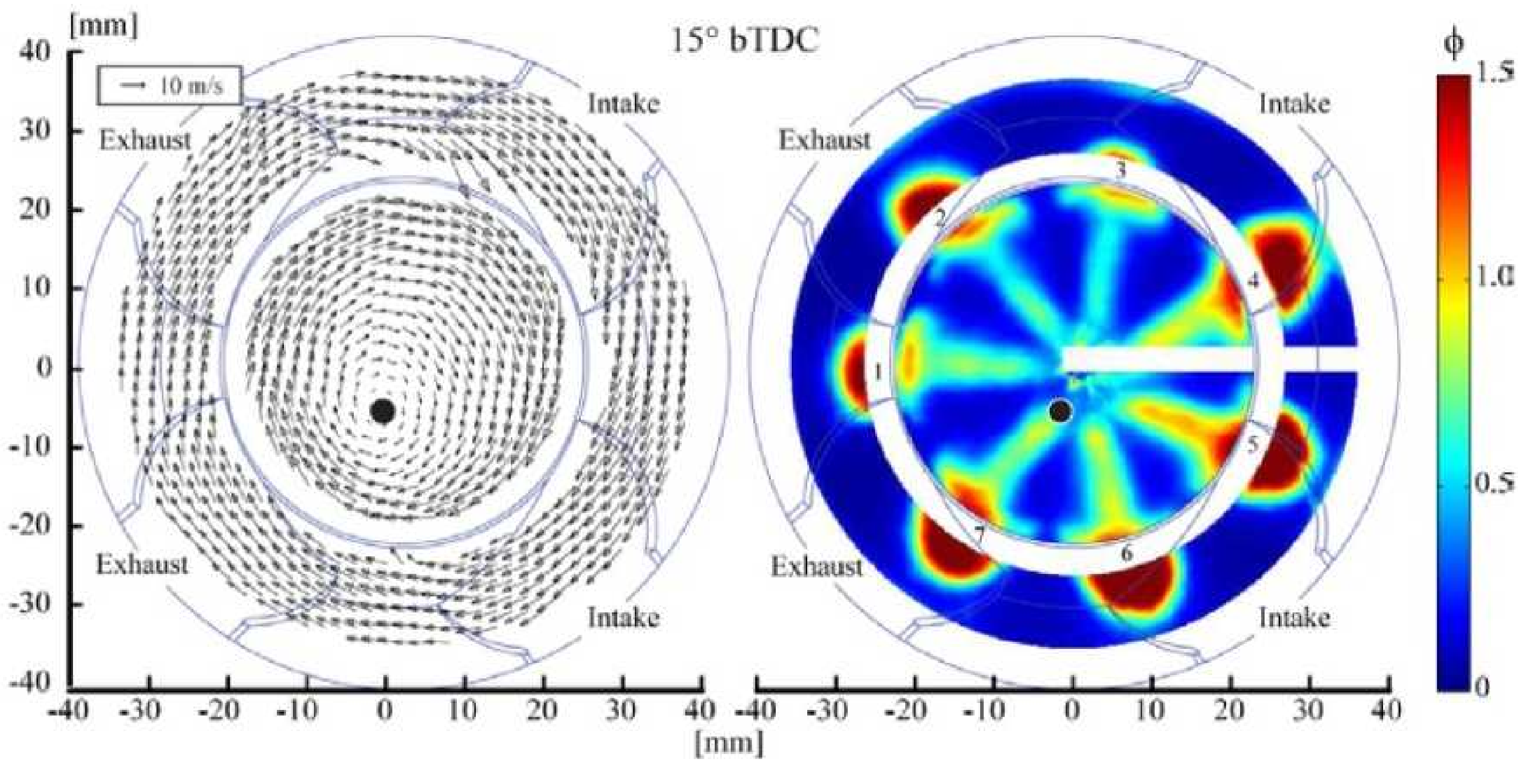
Outline

- 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
  - 3D CFD simulation with FRESCO
- Summary

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



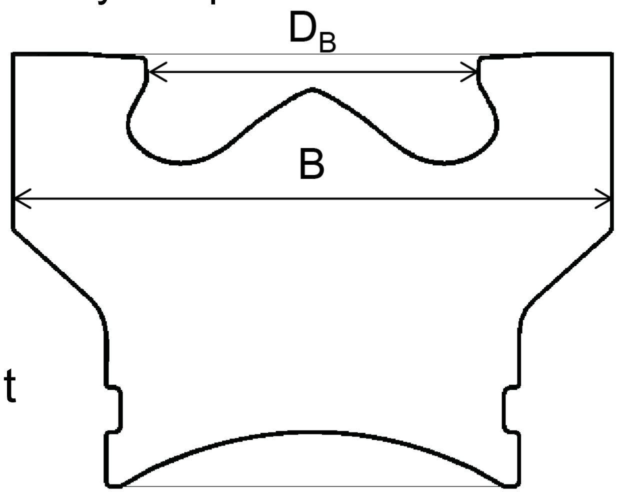
- Spray asymmetry is initiated by the asymmetric mean flow.

[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

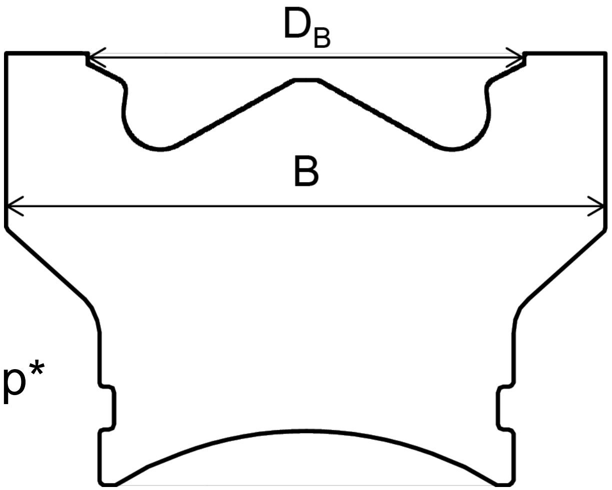
- Two piston bowl geometries with the same bowl volume available for in-cylinder flow asymmetry comparison.

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

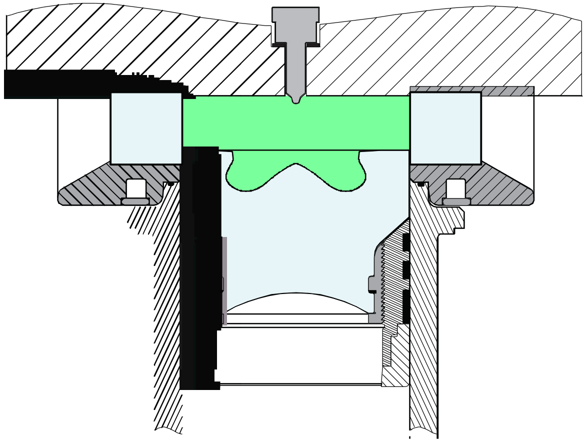
Stepped-lip*



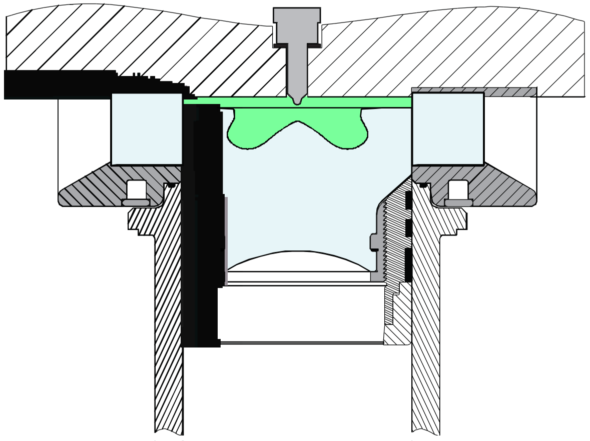
- Squish height (TDC) = 1.346 mm
- Compression ratio = 15.8
- Different optical distortion pattern
- No valve cut-outs
- Bowl to bore ratio: $D_B/B=0.73$
- 30% higher laser pulse energy
- Optimized laser sheet

* Kurtz, E. 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.

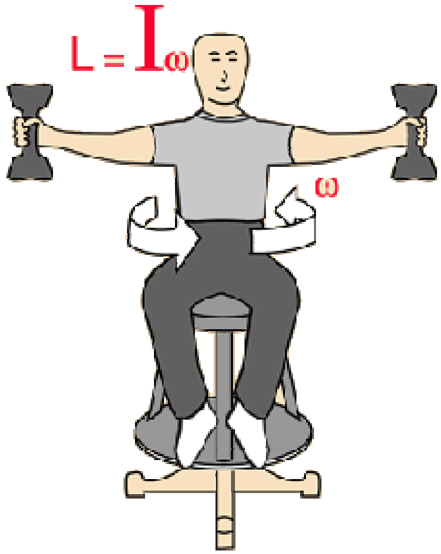
The moment of inertia of the cylinder contents decreases as they are pushed into the piston bowl.

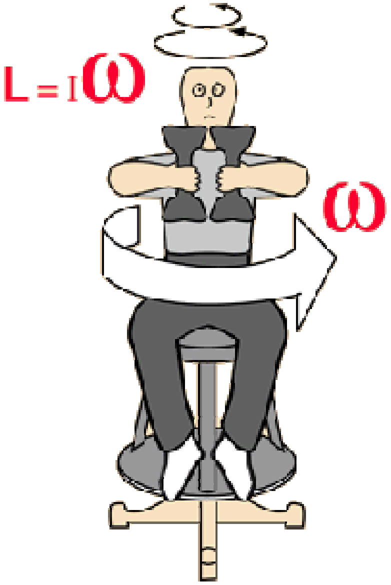


-50⁰aTDC



-20⁰aTDC





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

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

$$L = I_z\omega \approx constant$$

↓ ↑

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

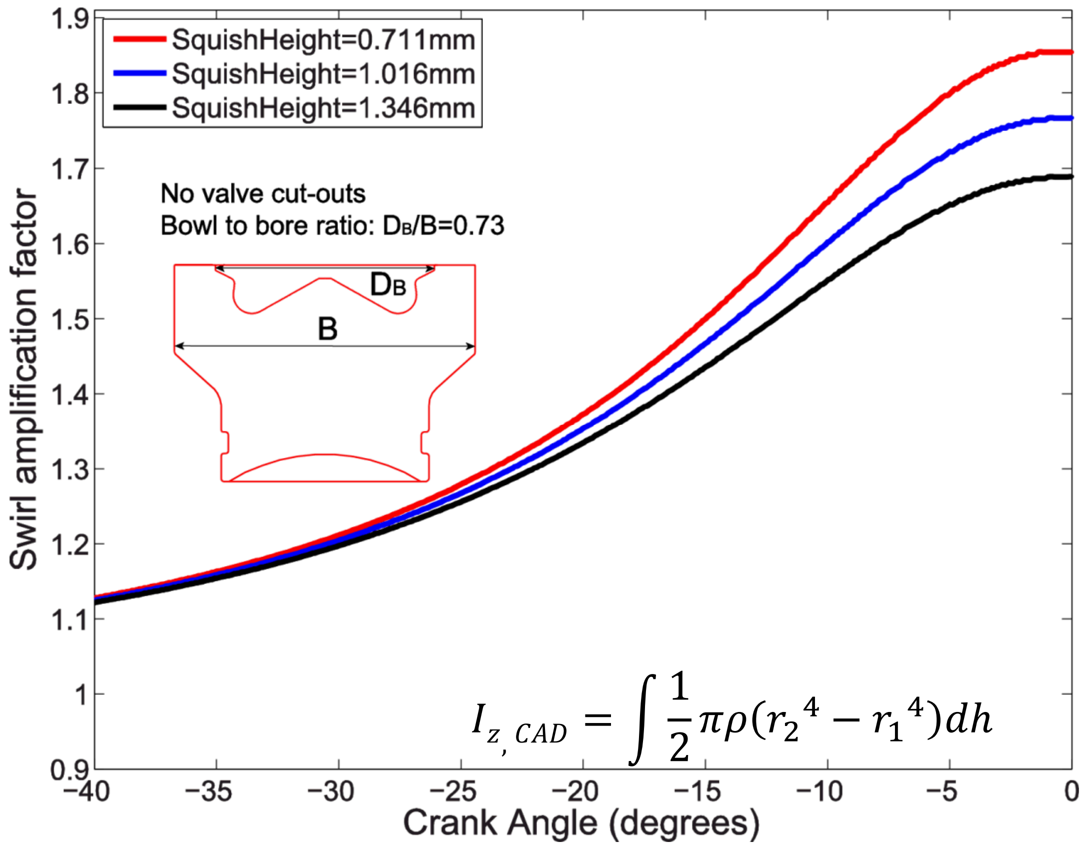
http://hyperphysics.phy-astr.gsu.edu/hbase/rstoo.html

Effect of Squish Height on Swirl Amplification

- 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.



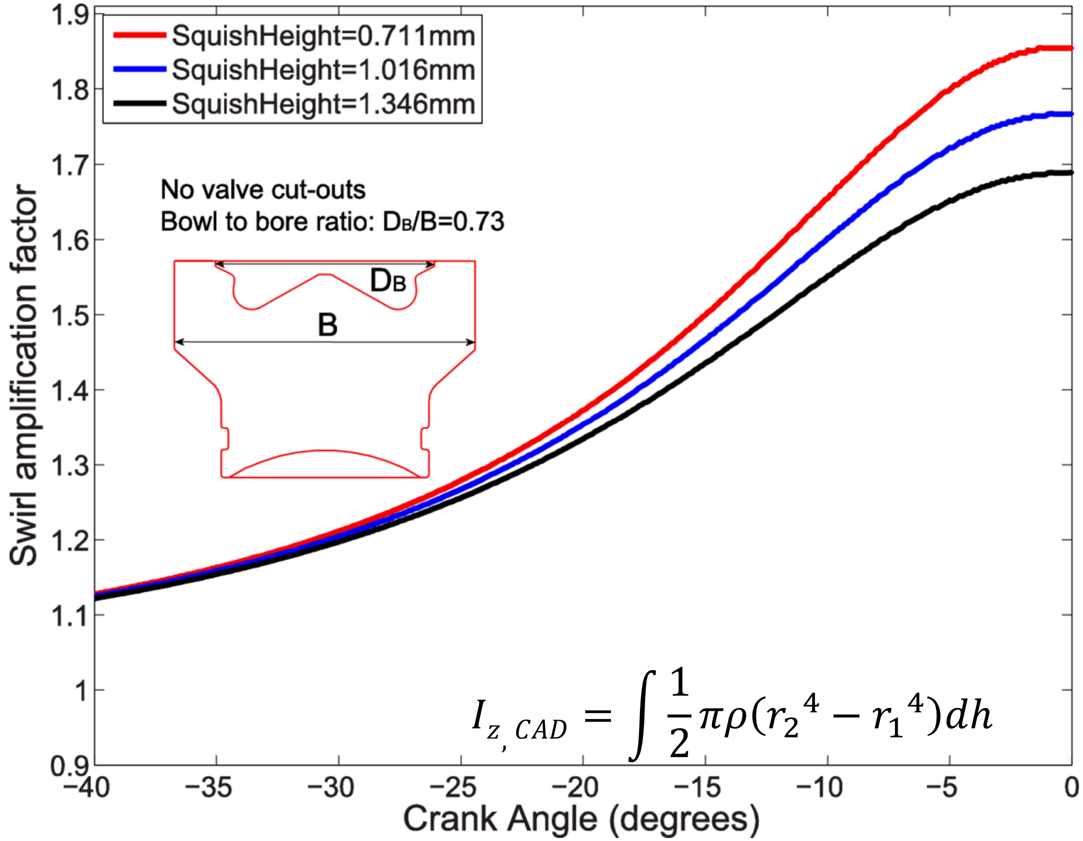
$$I_{z,CAD} = \int \frac{1}{2}\pi\rho({r_2}^4 - {r_1}^4)dh$$

Effect of Squish Height on Swirl Amplification

- 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.

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

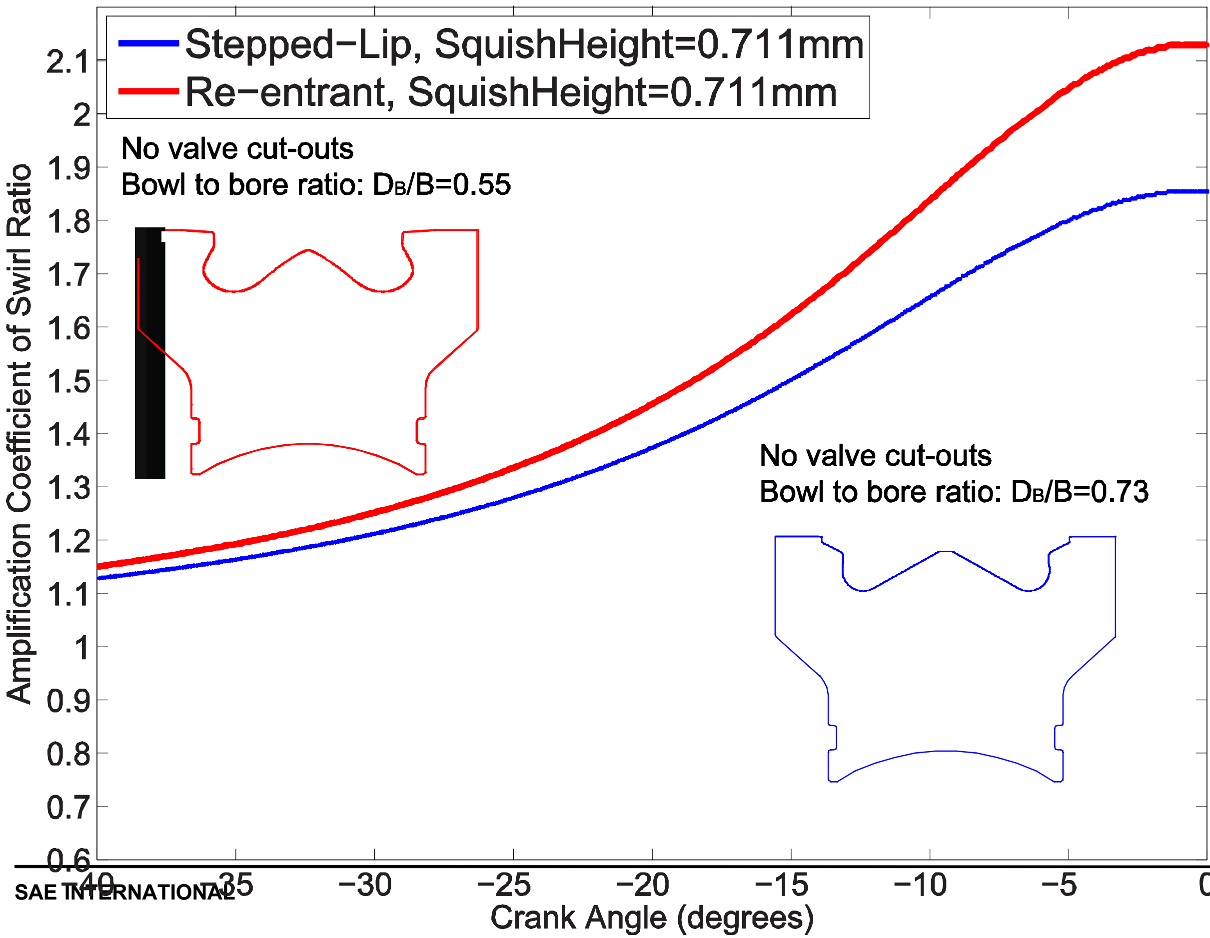
- The effect of squish height in swirl development is more obvious near TDC.
- Draw backs to this simplified analysis
  - Assumption: solid body rotation around cylinder axis
  - Impact of valve cut-outs are neglected
  - Influence from intake flow is neglected



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

Effect of Piston Geometry in Swirl Amplification

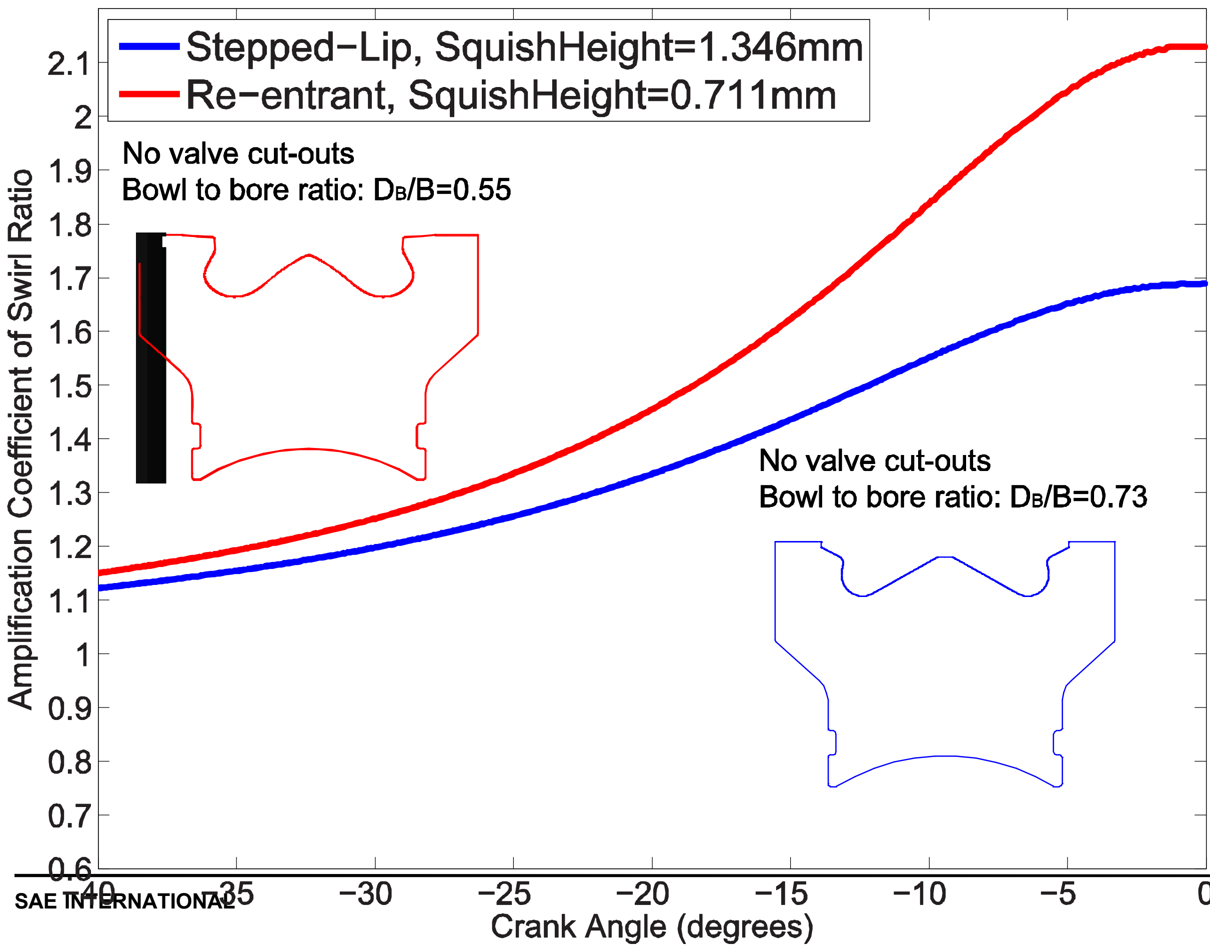
- With the same squish height and compression ratio, swirl amplification is less pronounced with the stepped-lip piston bowl which results in a temporal delay by 4.4 CAD(σ=2.9 CAD) from late compression until TDC.
- The temporal delay of swirl development increases with piston compression.



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

With larger squish height, swirl amplification effect for stepped-lip piston becomes even less pronounced than re-entrant piston after IVC.

- 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>
- Squish height for stepped-lip geometry is increased to avoid valve interference with flat piston top.

Broader bowl entrance geometry is the main reason for slower swirl amplification during compression stroke

charge density

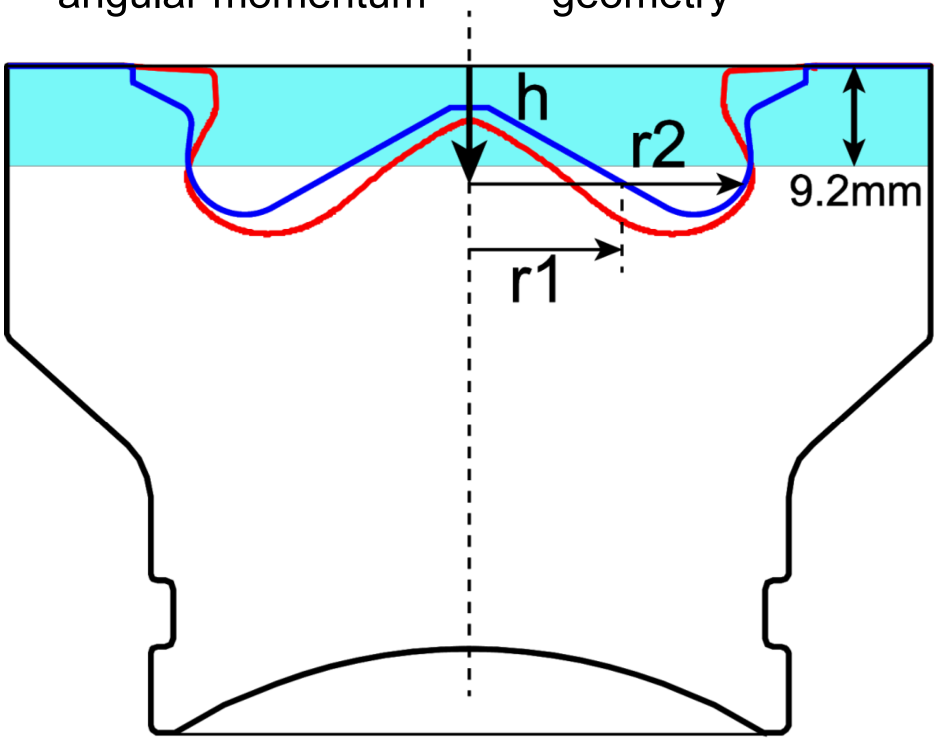
$$I_z = \frac{1}{2}\pi\rho \int (r_2{}^4 - r_1{}^4)\,dh$$

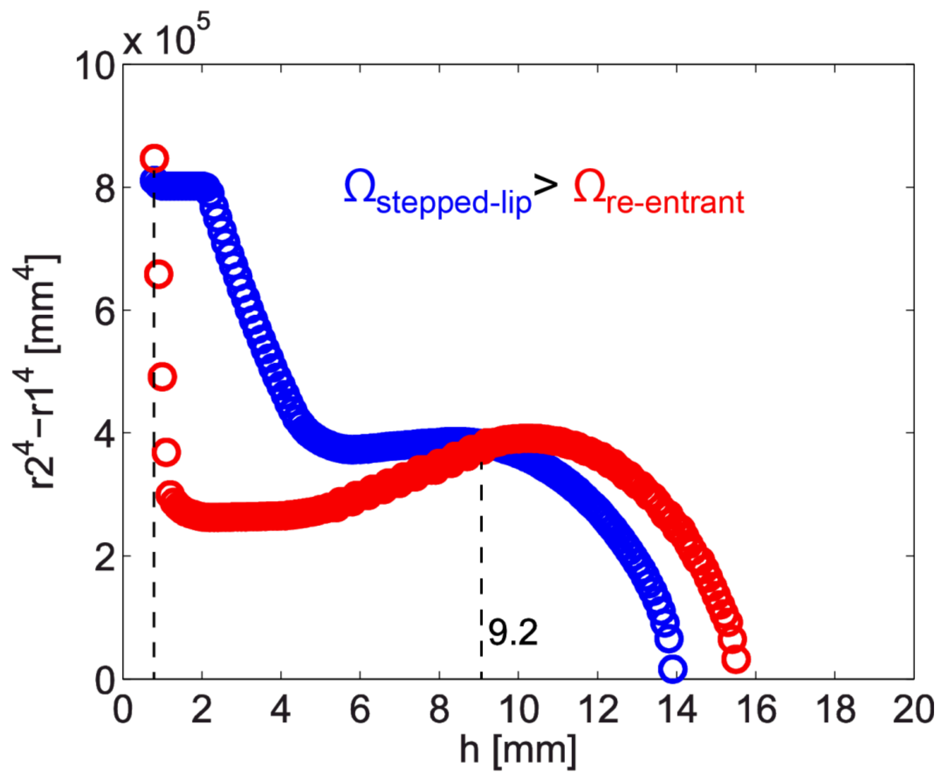
Ω

angular momentum

geometry

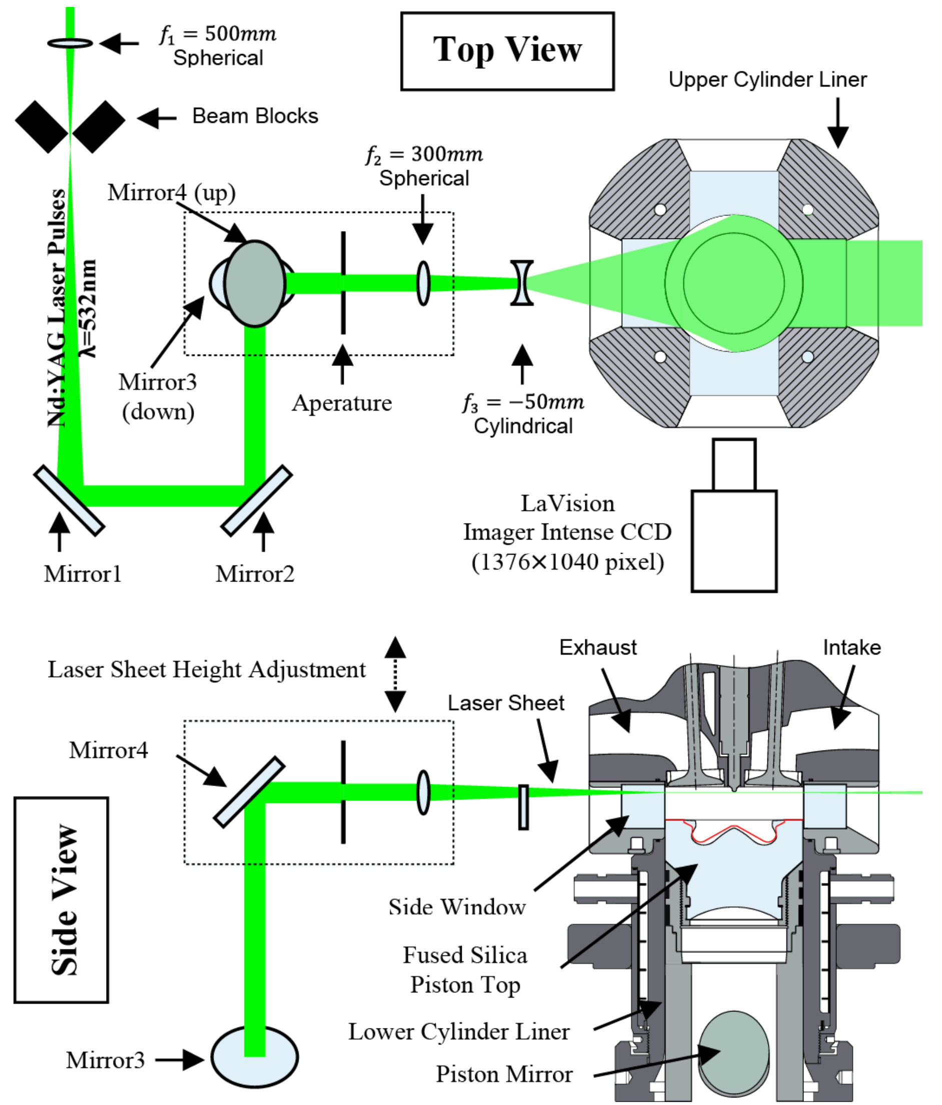
- Larger values of the integral $\Omega = \int (r_2{}^4 - r_1{}^4)dh$ means the swirl develops more slowly.





Swirl-Plane PIV Measurement Setup and Test Cases

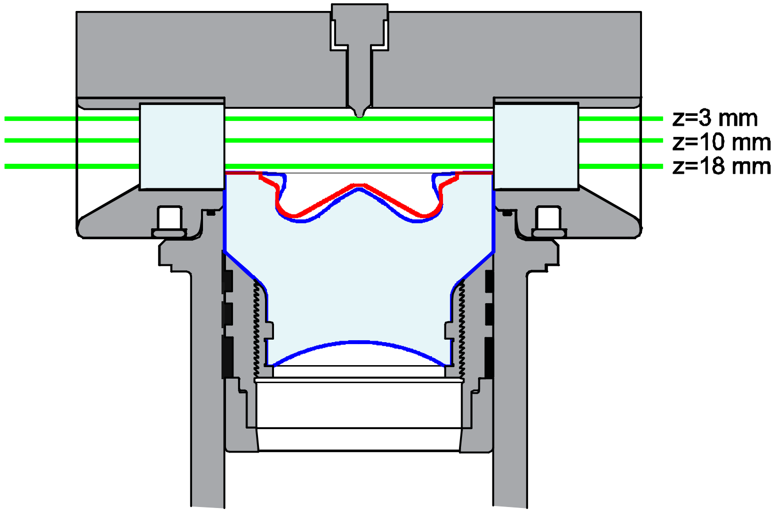
GM 1.9 L Diesel Engine	
Bore	82 mm
Stroke	90.4 mm
Displacement Volume	0.477 L
Geometric CR	16.7 (re-entrant) 15.8 (stepped-lip)
Squish Height	0.711 mm (re-entrant) 1.346 mm (stepped-lip)
Intake / Exhaust Valves	2 / 2
Steady-state swirl Ratio	1.5, 2.2, 3.5
Engine Speed	1500 rpm
Intake Pressure	1.5 bar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

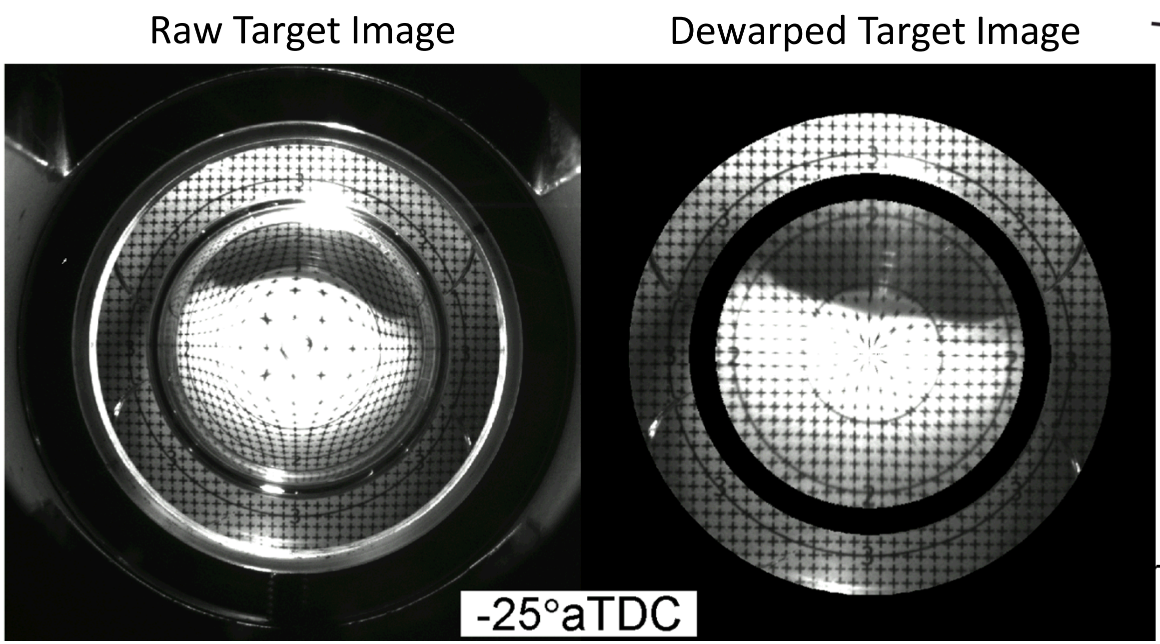


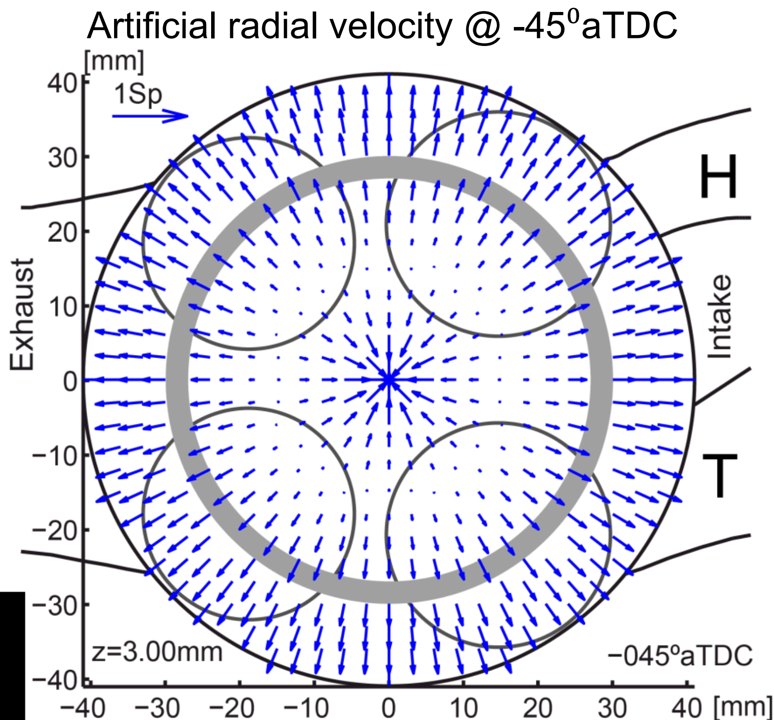
Test cases:

- 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.

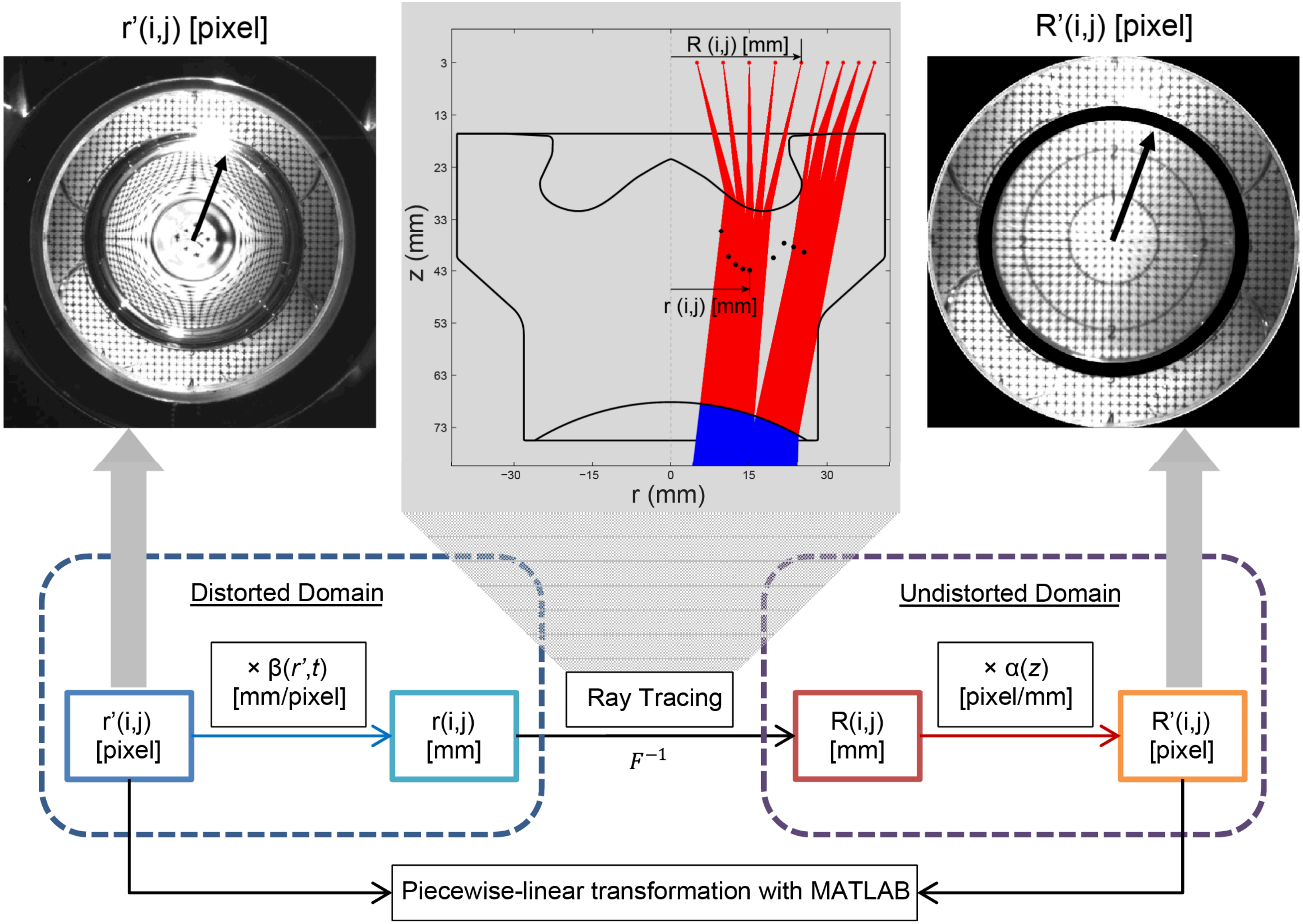






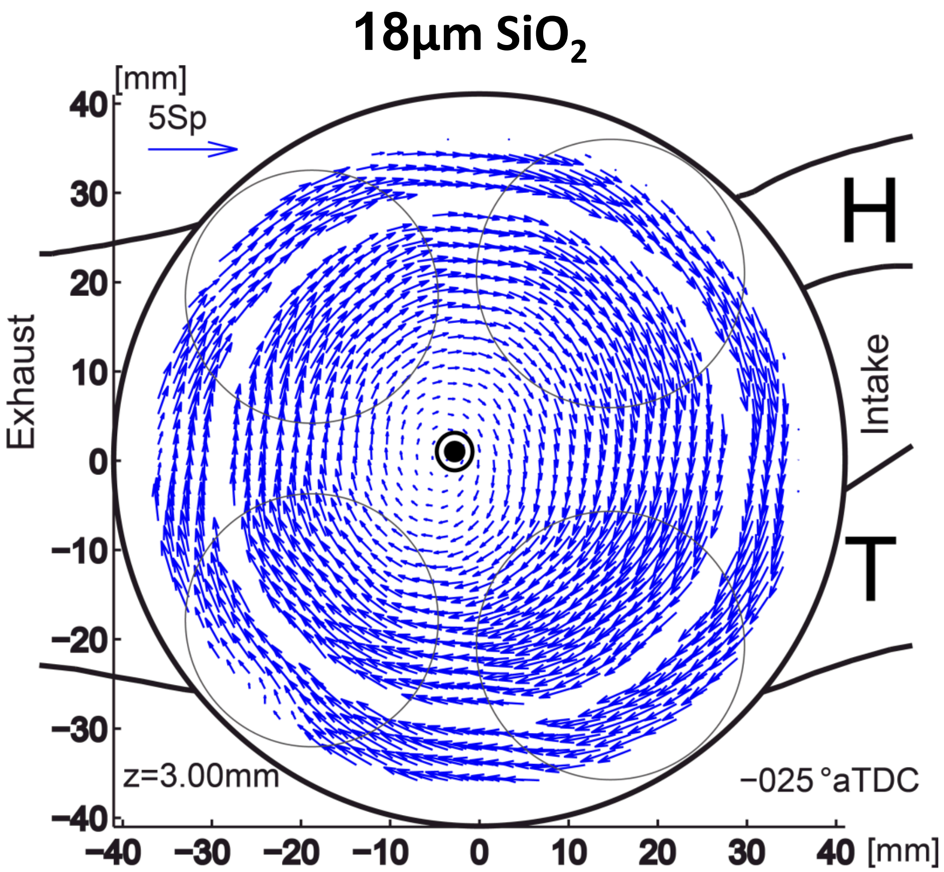
- Optical distortion induced by the piston is spatially and temporally dependent.
- Artificial radial velocity created by the incremental piston movement between two laser pulses is non-negligible.

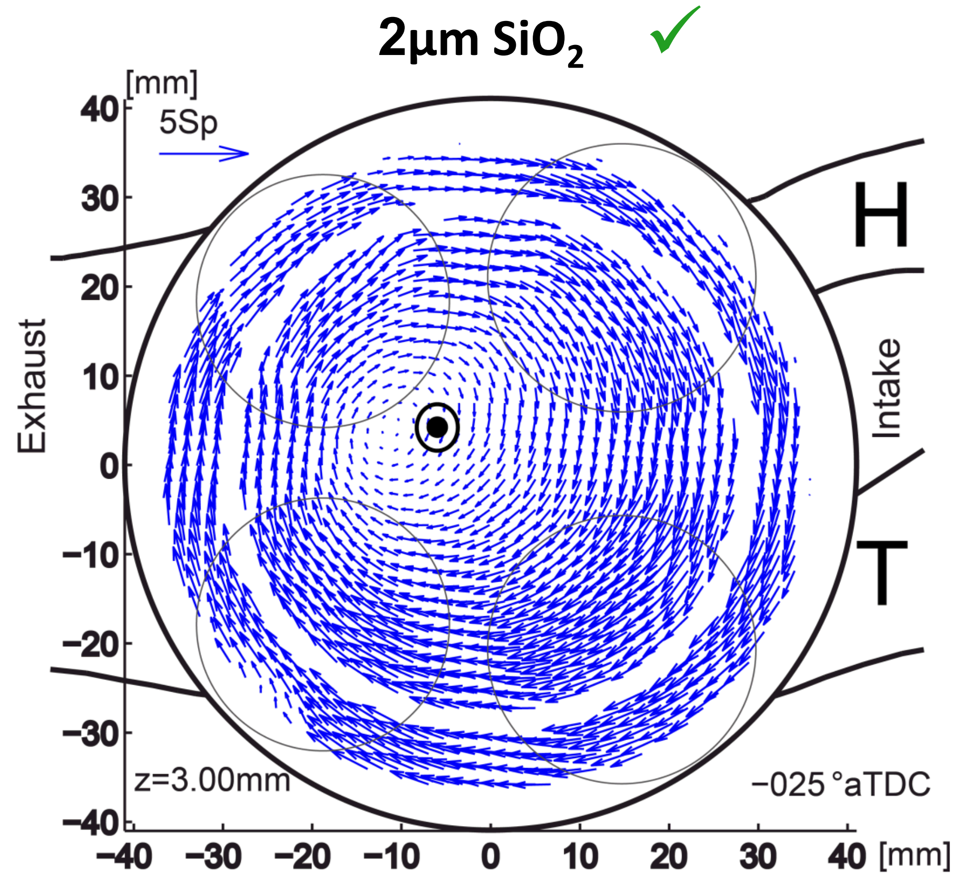
Ray tracing allows a full dewarping transformation with any given laser plane position and piston location.



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.

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





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

  σ_x=2.0 mm, σ_y=2.1 mm

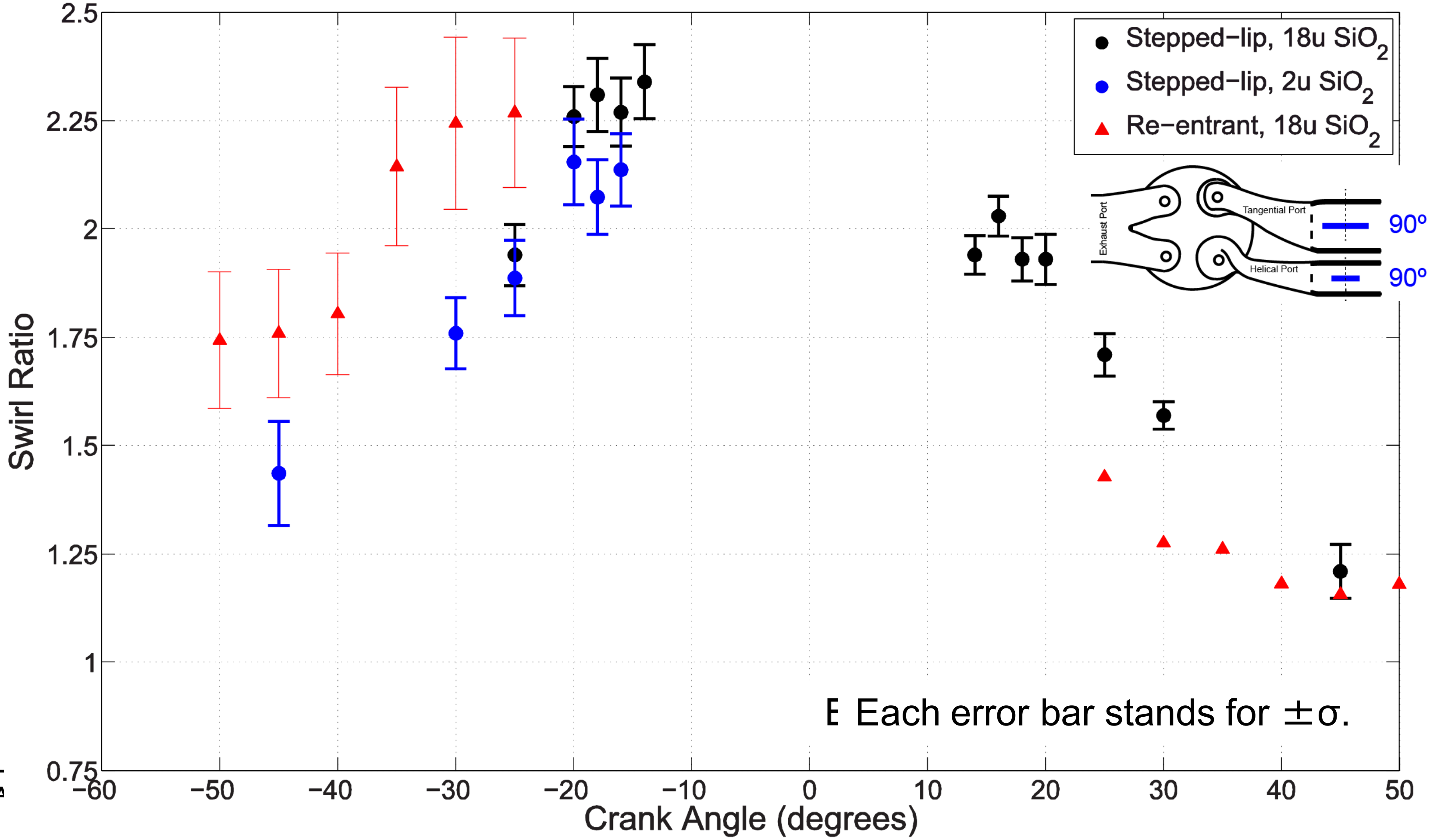
- Mean swirl center location: [-5.9, 4.1] mm

  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.

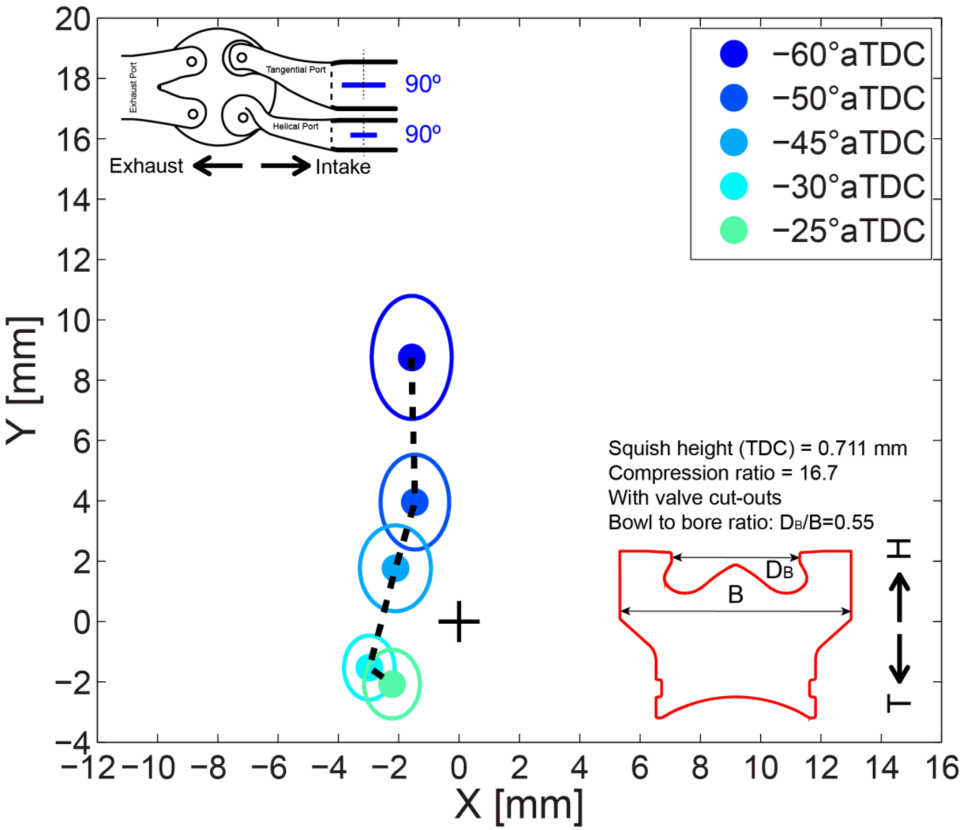
During compression stroke until -25^{0}aTDC, swirl develops slower with stepped-lip piston geometry than with the re-entrant bowl geometry.

- 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.

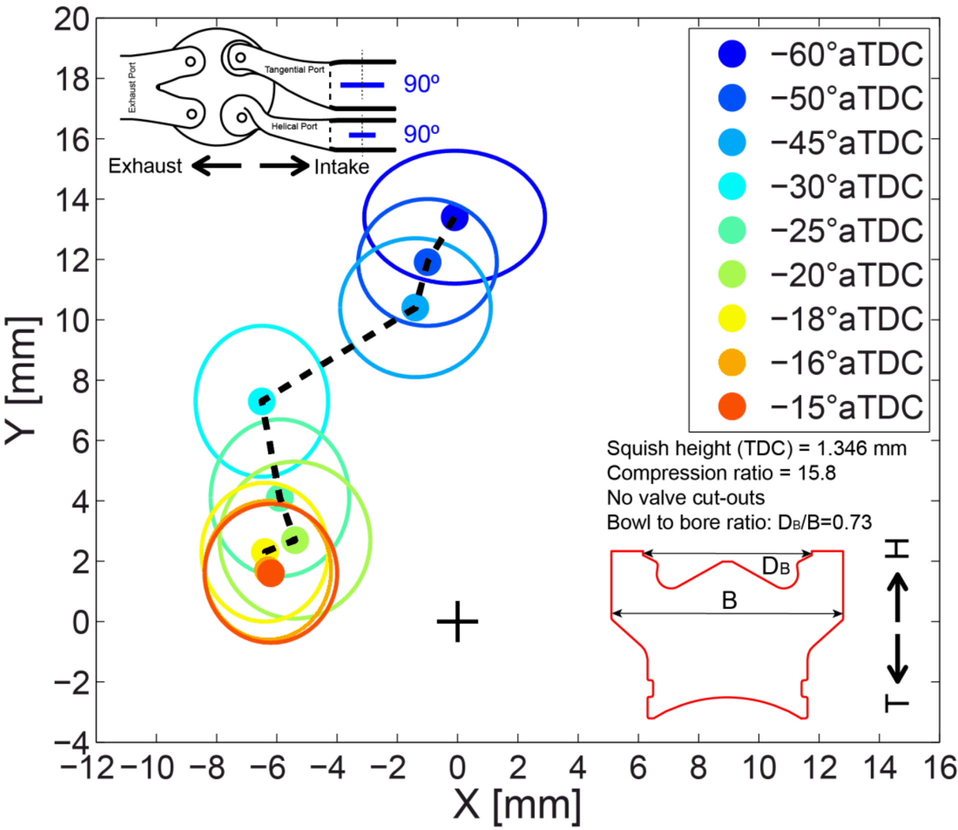


In-cylinder swirl with stepped-lip piston is more eccentric.

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



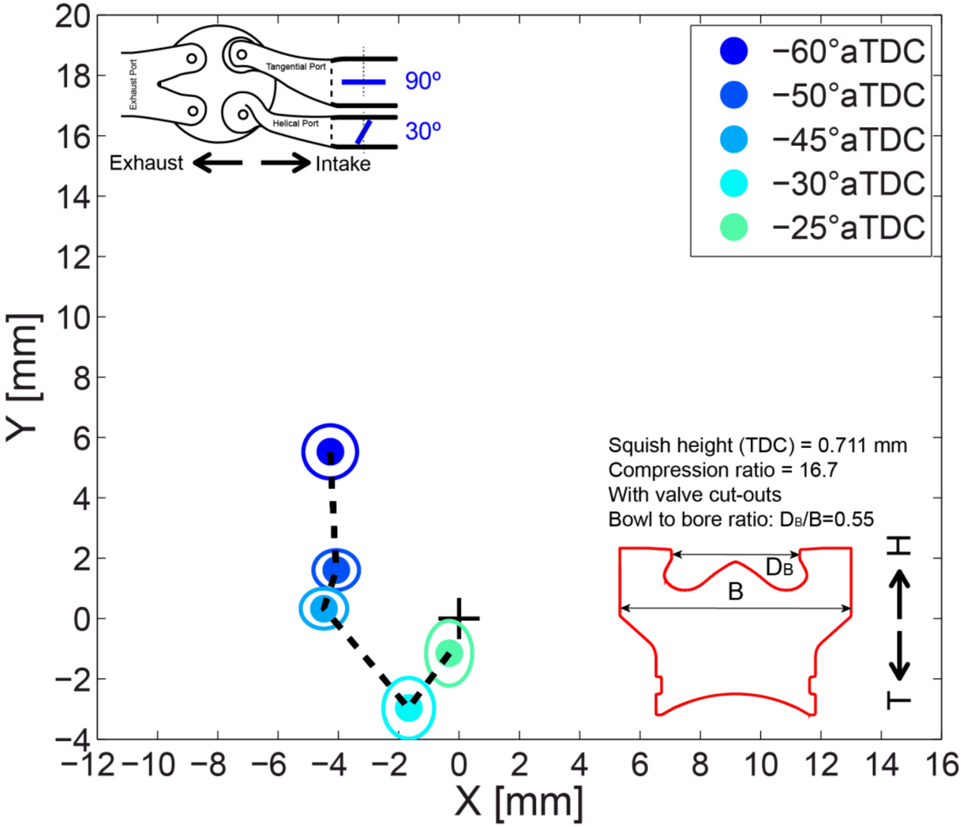
Stepped-lip piston bowl, $R_{s,steady}$=2.2



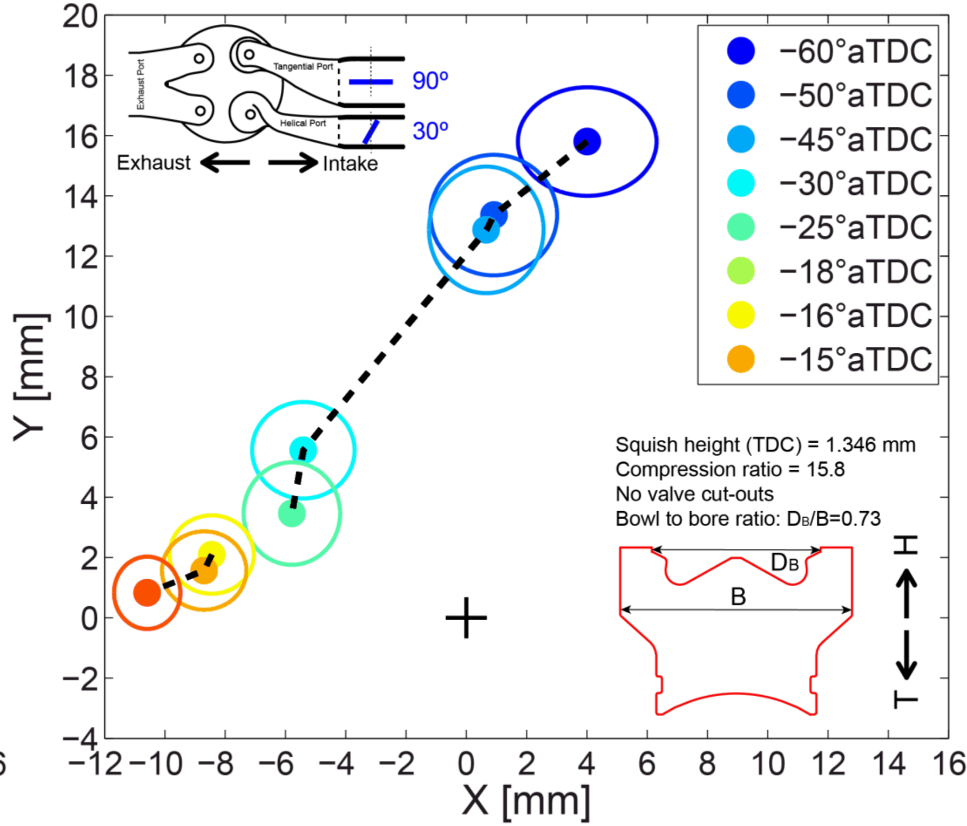
Each black ellipse indicates one σ of swirl center location away from the mean positions (out of 220 instantaneous velocity fields).

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



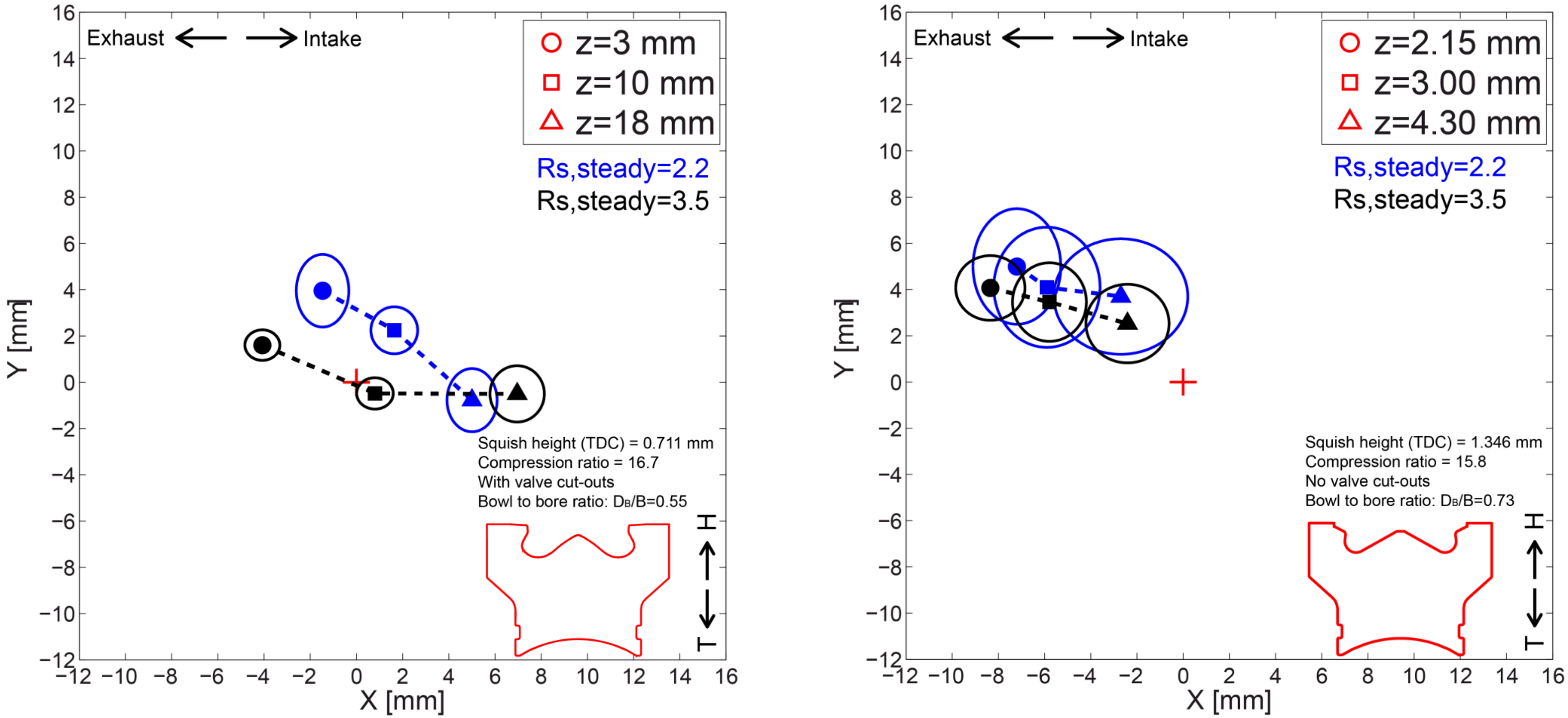
Stepped-lip piston bowl, $R_{s,steady}$=3.5



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**



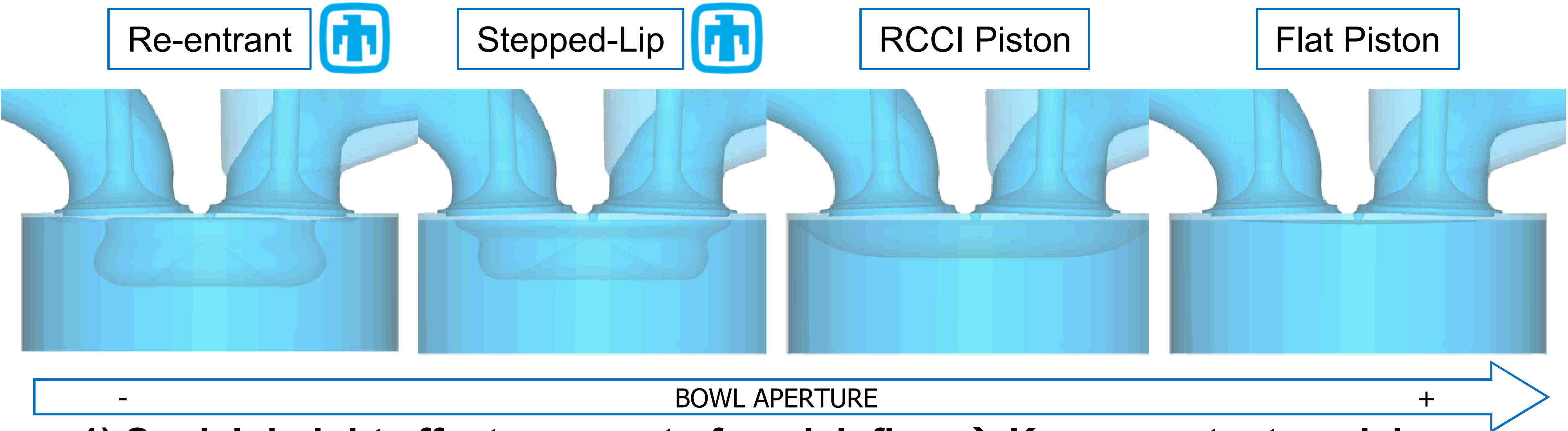
Each black ellipse indicates one σ of swirl center location away from the mean positions (out of 220 instantaneous velocity fields).

3D CFD simulation with FRESCO

University of Wisconsin -- Engine Research Center

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

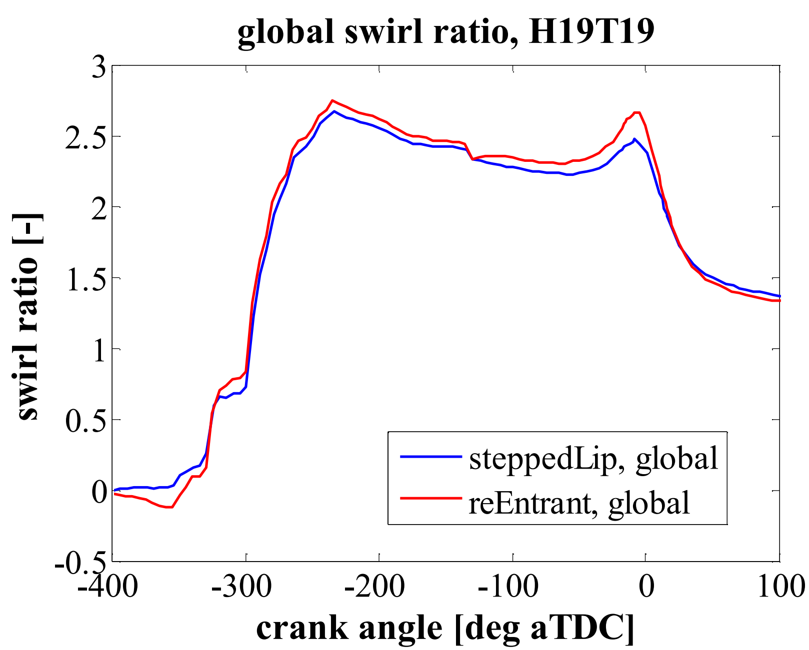
by **FRESCO**

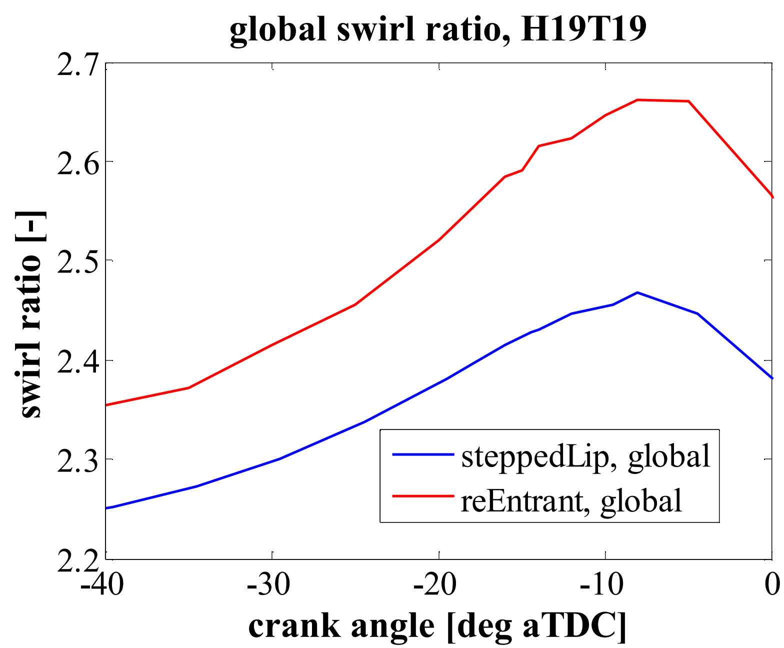


1) **Squish height affects amount of squish flow → Keep constant squish height instead of compression ratio**

2) **Analyze effects of squish height on flow structure**

Global swirl ratio development

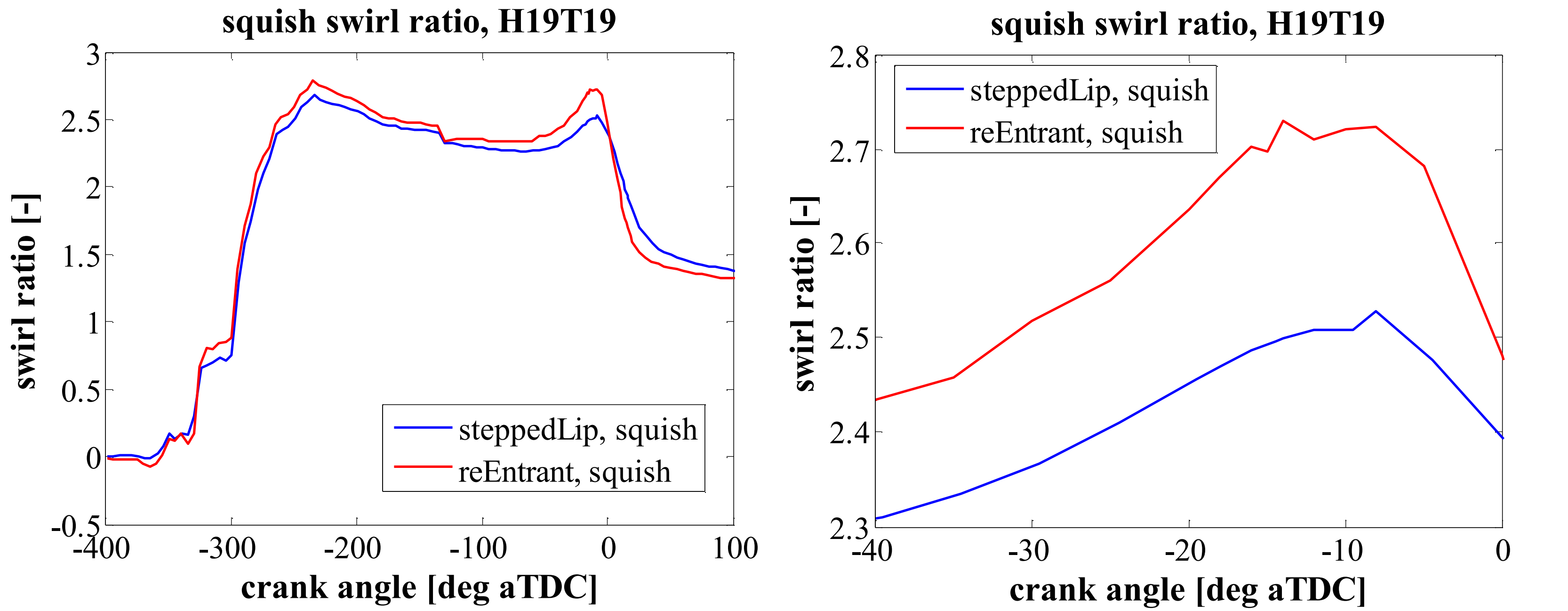




- Similar compression ratios but different squish heights are used: CR=16.7, s=0.78 mm for the re-entrant geometry, and CR=16.1, s=1.36 mm for the stepped-lip geometry

- The re-entrant piston shows a globally slightly stronger swirl amplification near TDC than the stepped-Lip. The global Rs values are directly linked with the higher CR

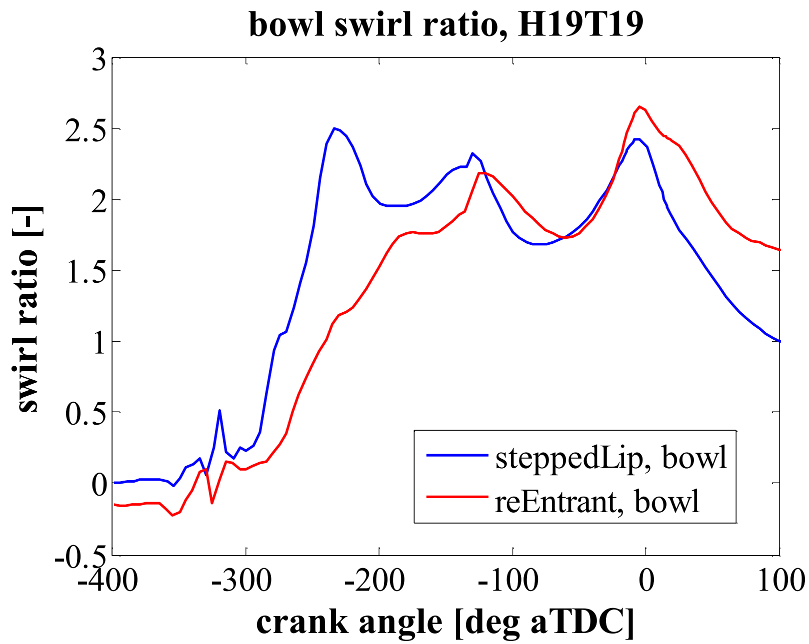
Squish swirl ratio development

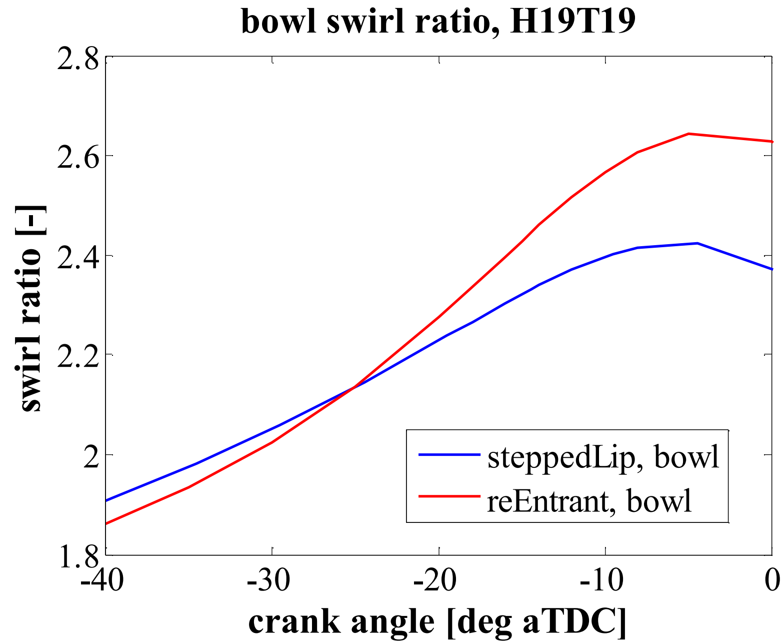


- Swirl ratio development in the squish region is a direct consequence of:
1) Compression ratio
2) Amount of swirling charge (not) transferred to the bowl due to squish flow

- The re-entrant piston shows slightly larger swirl amplification in the squish near TDC. This conveys that a more 'isolated' bowl receives less swirling momentum from the compression effect. This effect is much more evident in the no-cutouts configuration (not plotted here), where no geometry features interfere with the vortex motion

Bowl swirl ratio development





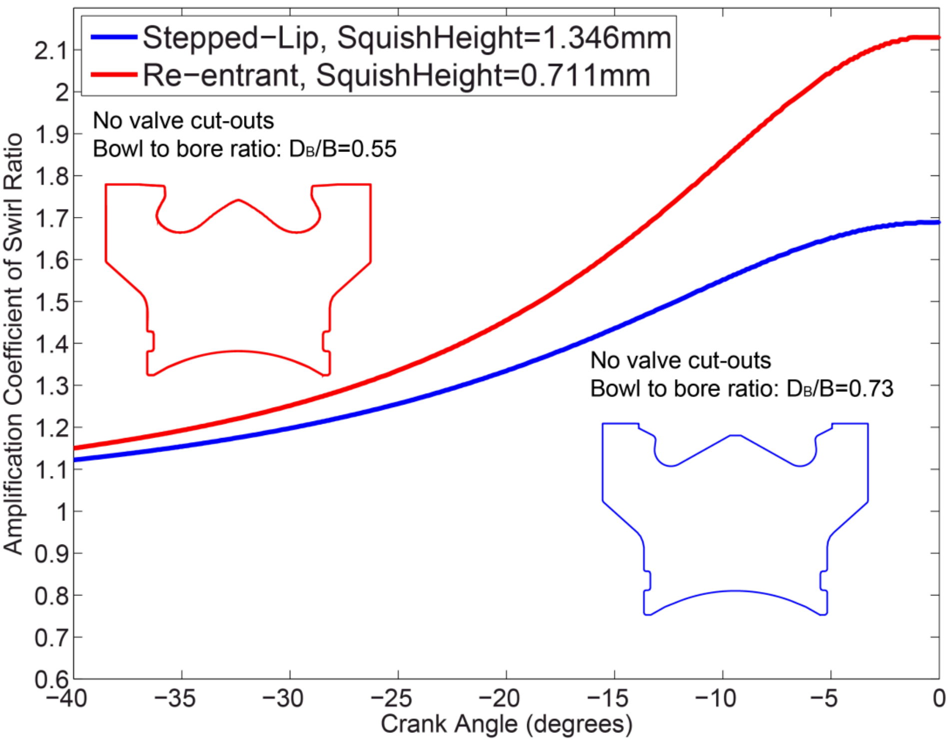
- Stepped-lip geometry has a substantially higher Rs throughout the intake stroke → Its more open bowl shape foster continuity between the squish and the bowl region (see previous slides)

- Stronger swirl amplification due to near-TDC compression is seen for the reEntrant bowl, which TDC squish height is more than 40% lower than for the steppedLip bowl → This seems to stress that most of the swirling momentum in the reEntrant bowl is achieved through the squish (swirl amplification) mechanism; the steppedLip bowl instead backs up the smaller squish contribution with a more sustained swirl vortex in the bowl during the intake stroke.

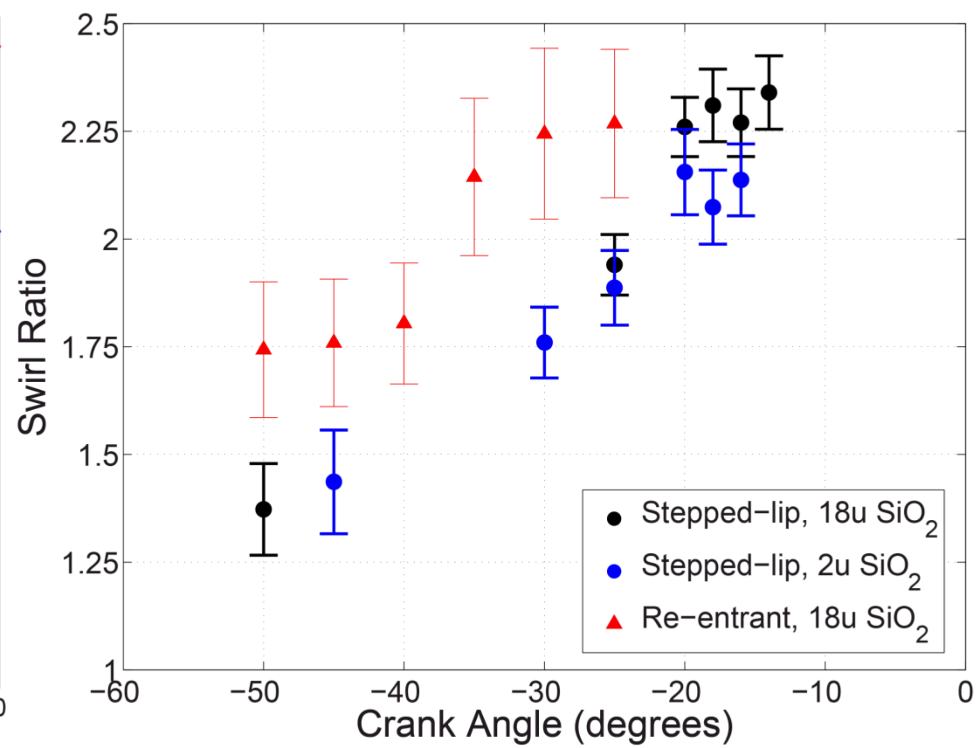
Summary/Conclusions

- 1-D simulation based on angular momentum conservation demonstrates the swirl amplification mechanism for 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.

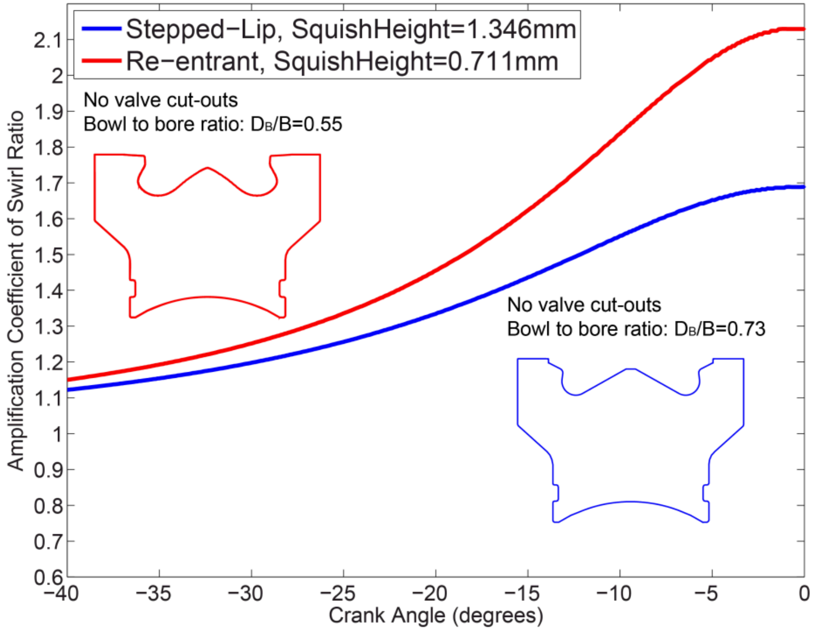
1-D Simulation

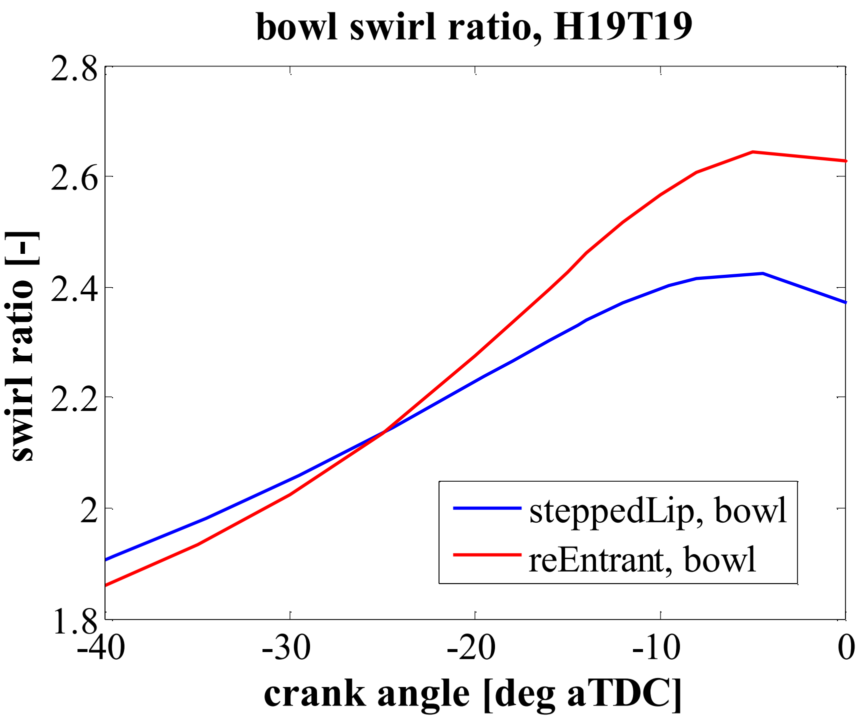


Experimental Results from PIV



Stronger swirl amplification for re-entrant bowl has been observed with both 1-D and 3-D simulation



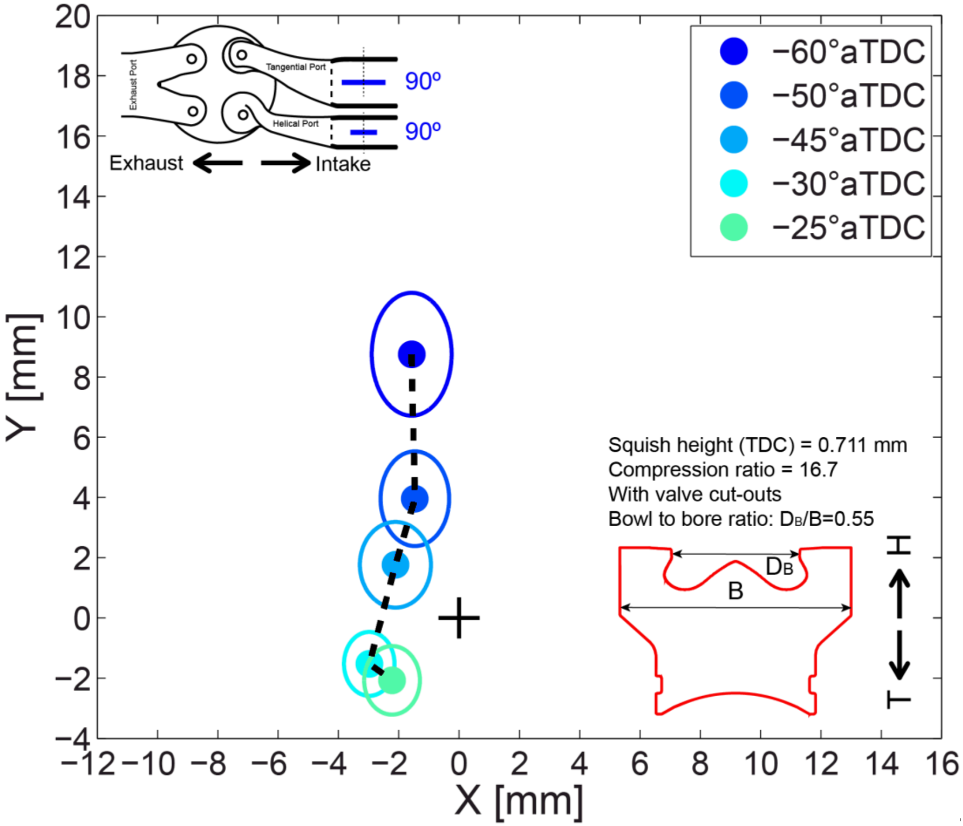


- Stronger swirl amplification due to near-TDC compression is seen for the reEntrant bowl, which TDC squish height is >40% lower than for the steppedLip bowl → This seems to stress that most of the swirling momentum in the reEntrant bowl is achieved through the squish mechanism; the steppedLip bowl instead backs up the smaller squish contribution with a more sustained swirl vortex in the bowl during the intake

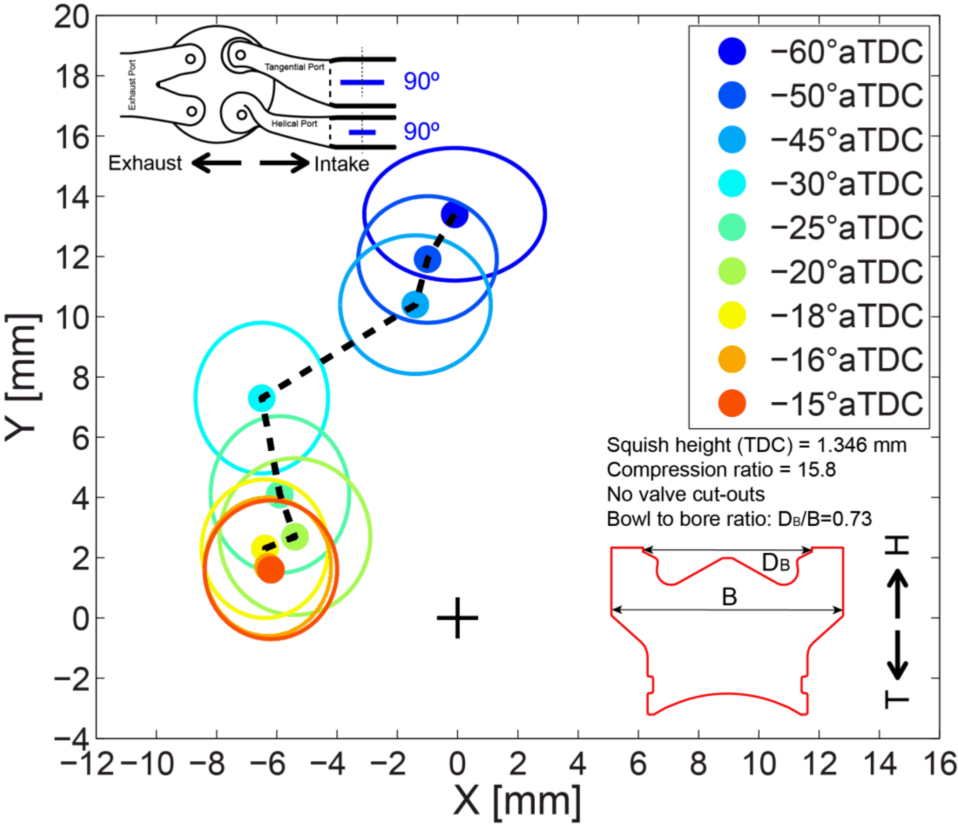
Summary/Conclusions

- 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

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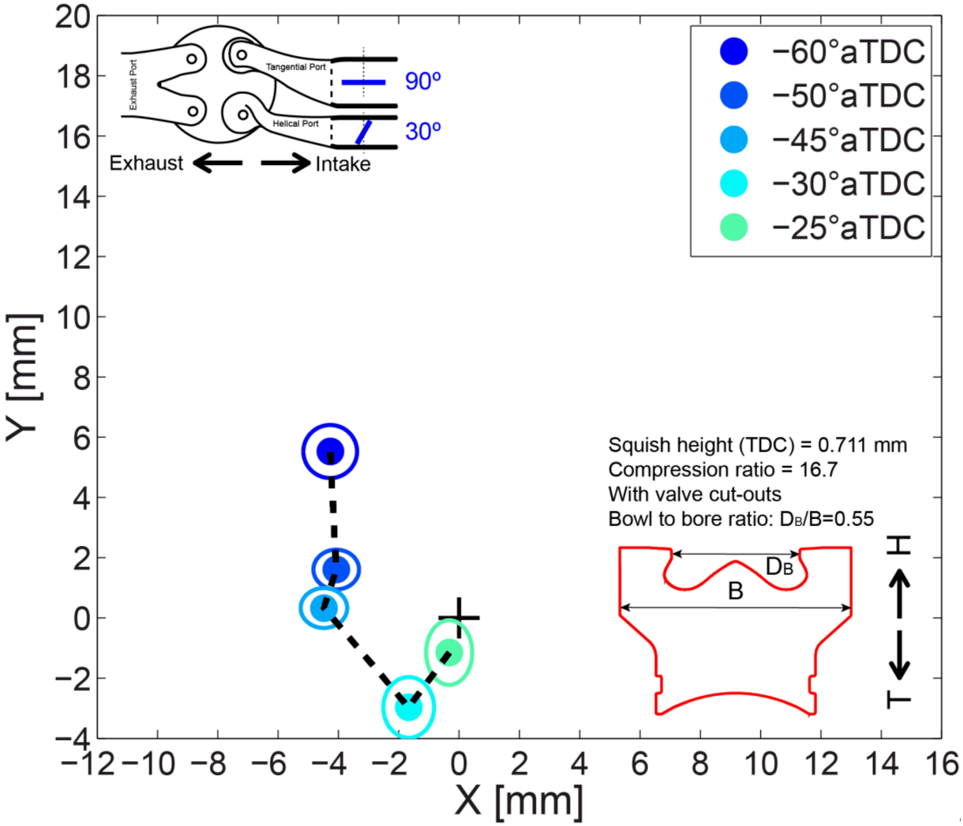
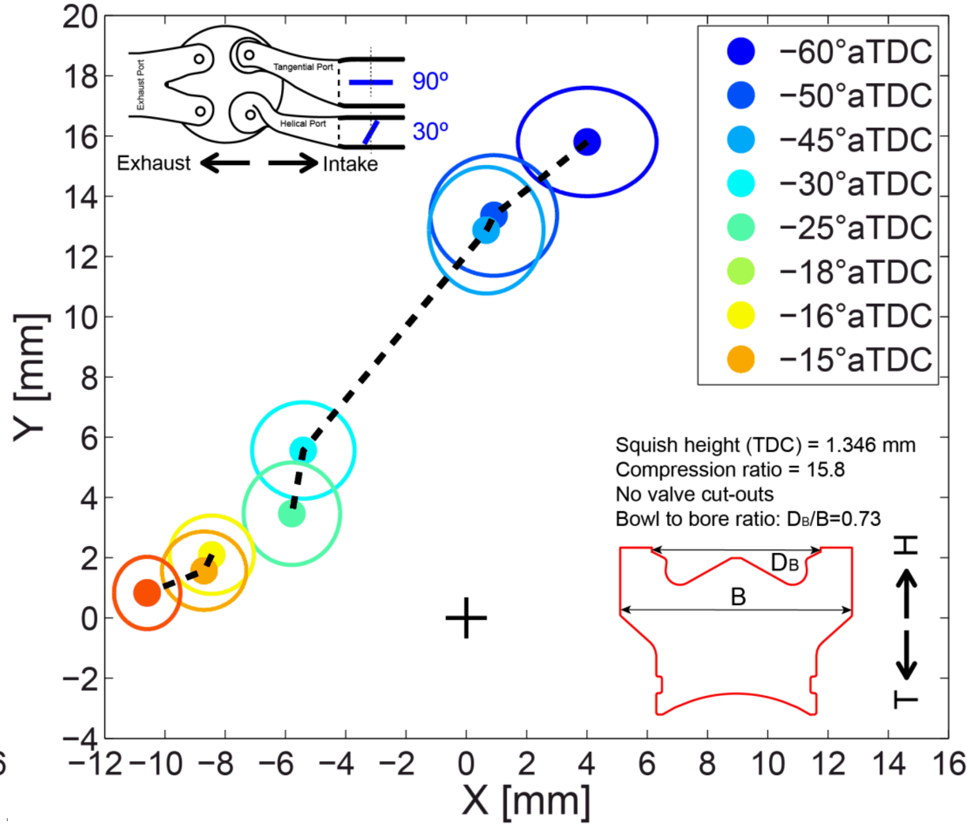
Re-entrant piston bowl, $R_{s,steady}$=3.5



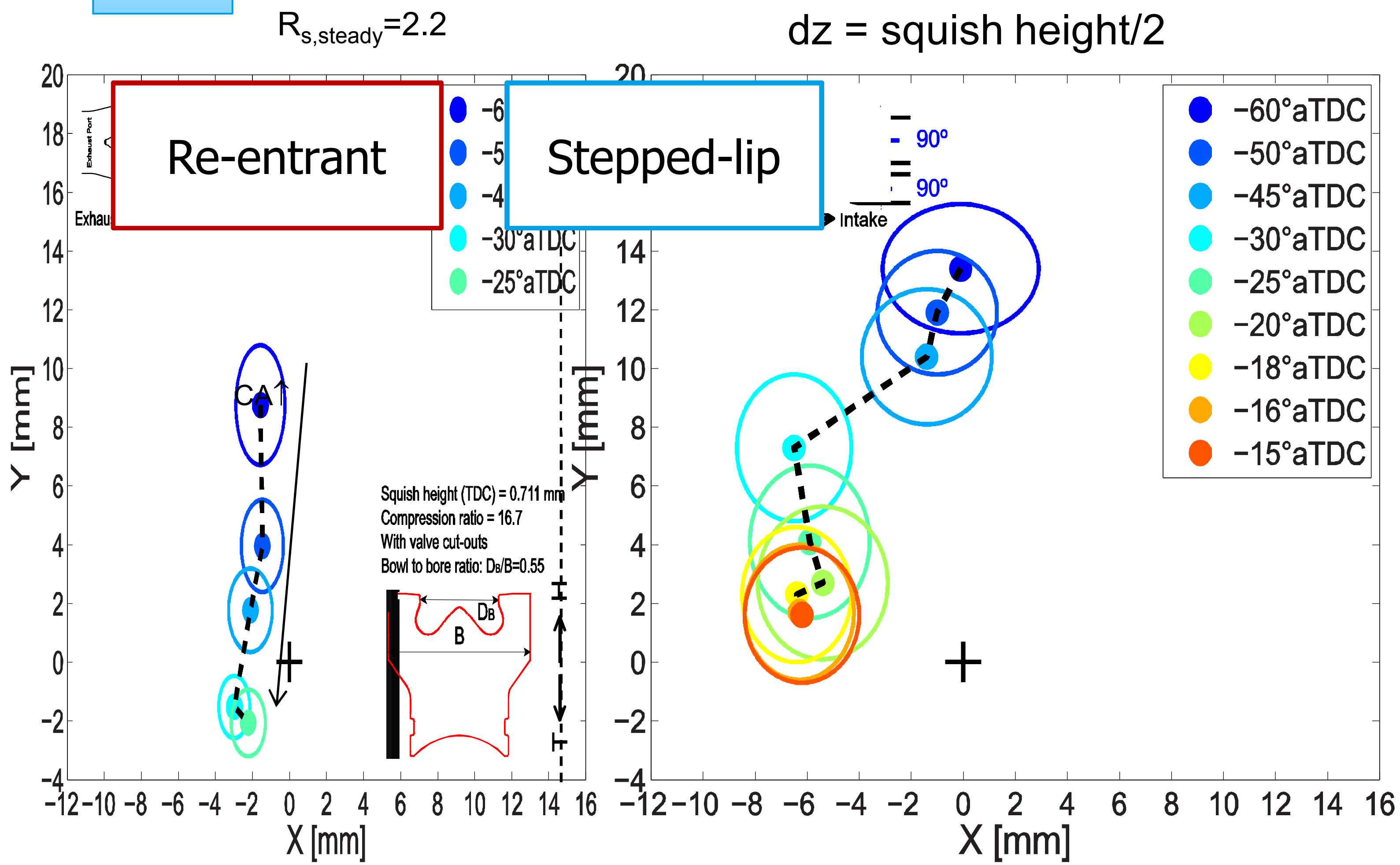
Stepped-lip piston bowl, $R_{s,steady}$=3.5



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

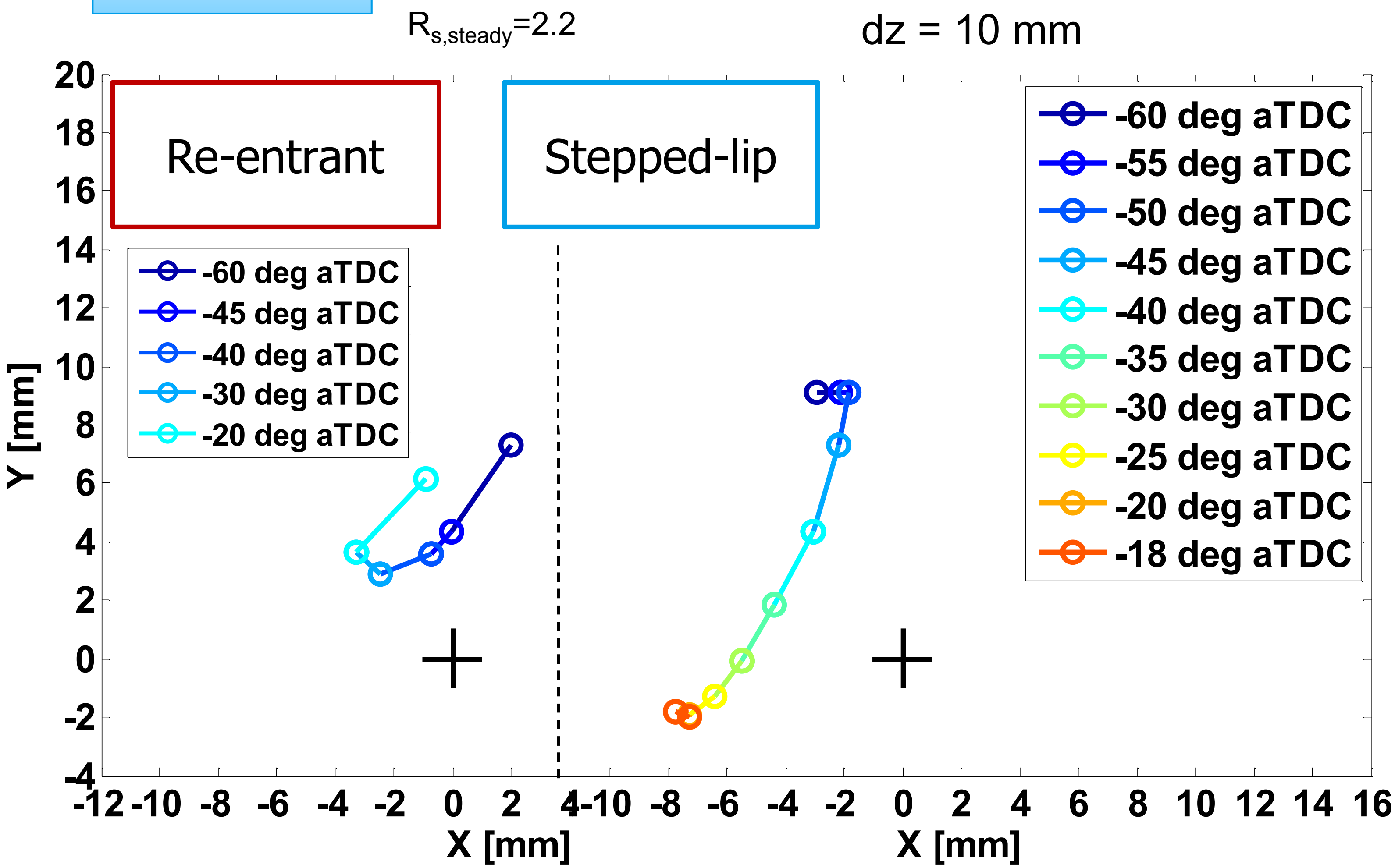
Summary/Conclusions

PIV



Summary/Conclusions

FRESCO



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- Gurpreet Singh, VTO program manager.
- Leo Breton, VTO technology manager.

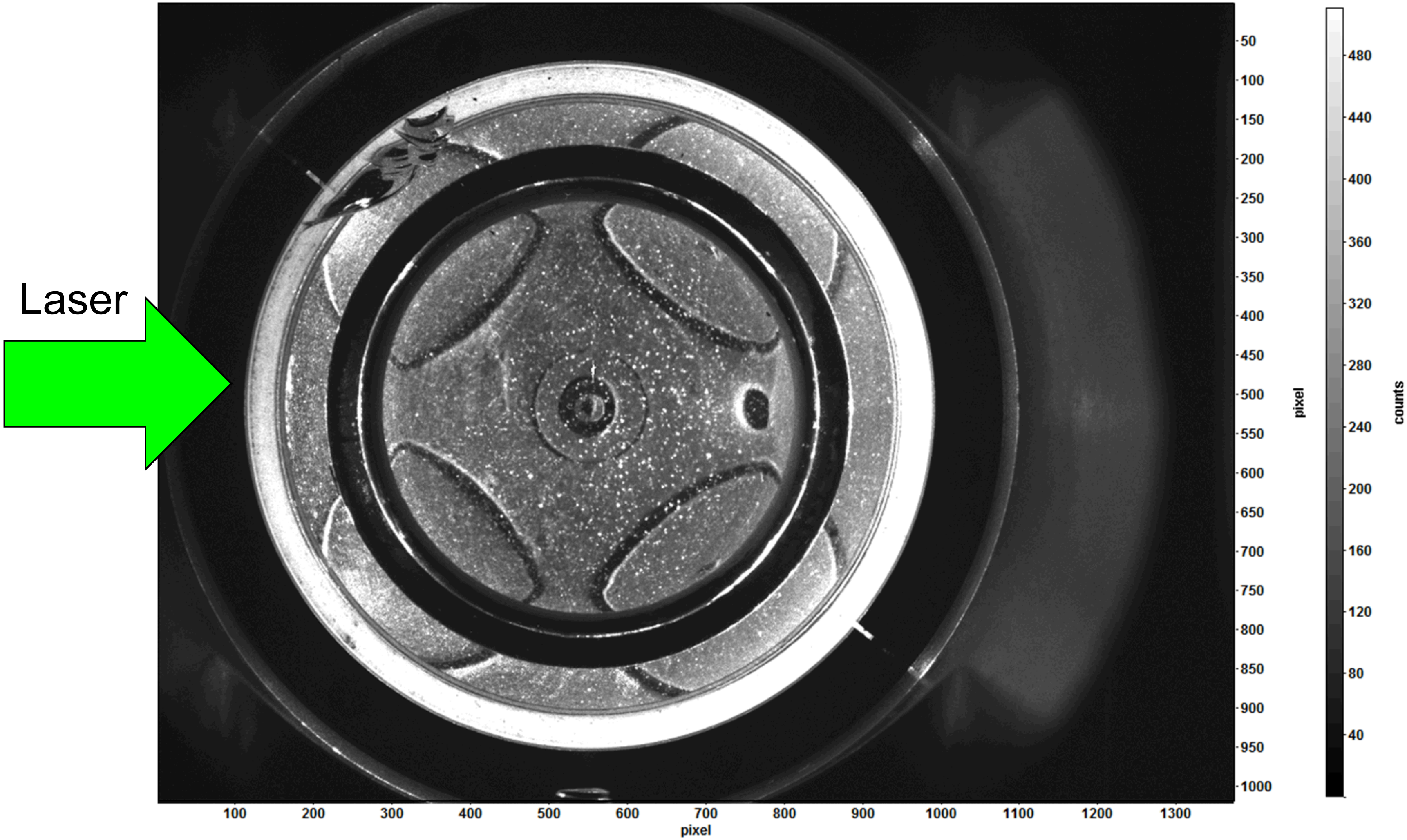
- Ken St. Hilaire and Tim Gilberson, Sandia R&D technologist.
- Katheryn Barker, Sandia office management assistant.

THANK YOU FOR YOUR ATTENTION !

QUESTIONS?

A demonstration of planar PIV experiments inside a swirl-supported light-duty optical Diesel engine with a realistic piston geometry

18µm SiO_2, -20°aTDC, z=2.5mm



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

18μm SiO_2, -0°aTDC, z=0.67mm