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A Study of Piston Geometry Effects on Late-Stage Combustion in a Light-Duty Optical Diesel Engine using Combustion Image Velocimetry

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Abstract

It is well known in engine community that piston bowl geometry may significantly impact the fuel efficiency and emissions for light-duty direct-injection Diesel engines. There exists two competing bowl geometries in the market, one is a conventional re-entrant bowl, the other geometry features a stepped-lip bowl and often a larger bowl-to-bore ratio. The performances of these two piston geometries are substantially different. However, the mechanisms responsible for these differences are not fully understood. In order to gain fundamental understanding of the piston geometry effect on in-cylinder processes and assist in the development of predictive engine simulation model, non-intrusive in-situ in-cylinder investigations are needed. This study investigates the piston geometry effect on late-stage combustion under medium load, conventional combustion regime. High-speed soot natural luminosity imaging is conducted in a single-cylinder light-duty optical Diesel engine with re-entrant and stepped-lip piston bowls, respectively. A combustion image velocimetry technique is utilized to quantify the in-cylinder macro-scale soot motion during the late-stage combustion.

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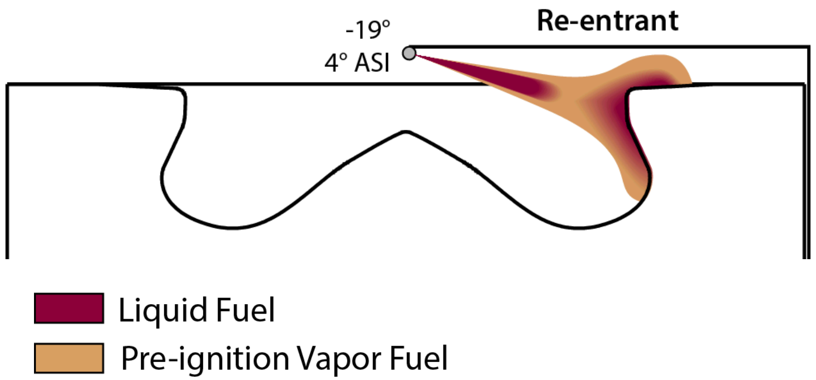
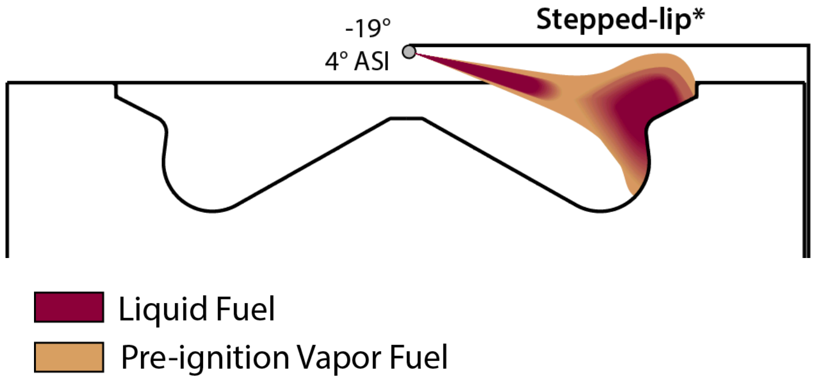
Outline

- Motivation
- Previous observations and analysis:
  - Metallic engine testing results
  - Thermodynamic analysis
  - Fuel tracer PLIF observation
- Introduction to combustion image velocimetry (CIV)
- Experimental setup
  - SNL optical piston bowl geometries
  - Conventional operating conditions and test matrix
  - Image Processing
- Results
- Summary
- Future Work

Motivation

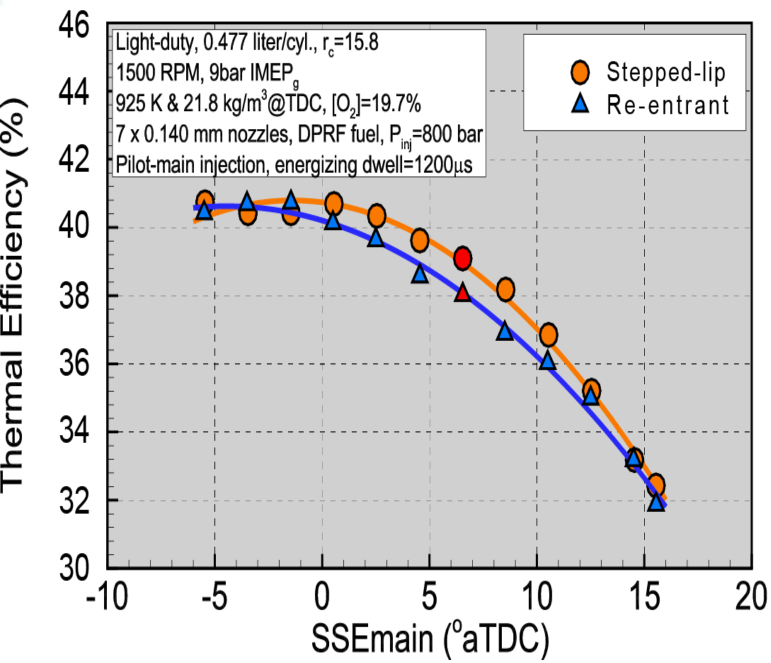
- This study: two substantially different piston bowls with geometries representative of existing technology.
- Fundamental understandings of piston geometry effects on in-cylinder processes (flow, mixture preparation, combustion) are needed.
- Reliable experimental datasets are needed for the development of predictive engine simulation model.

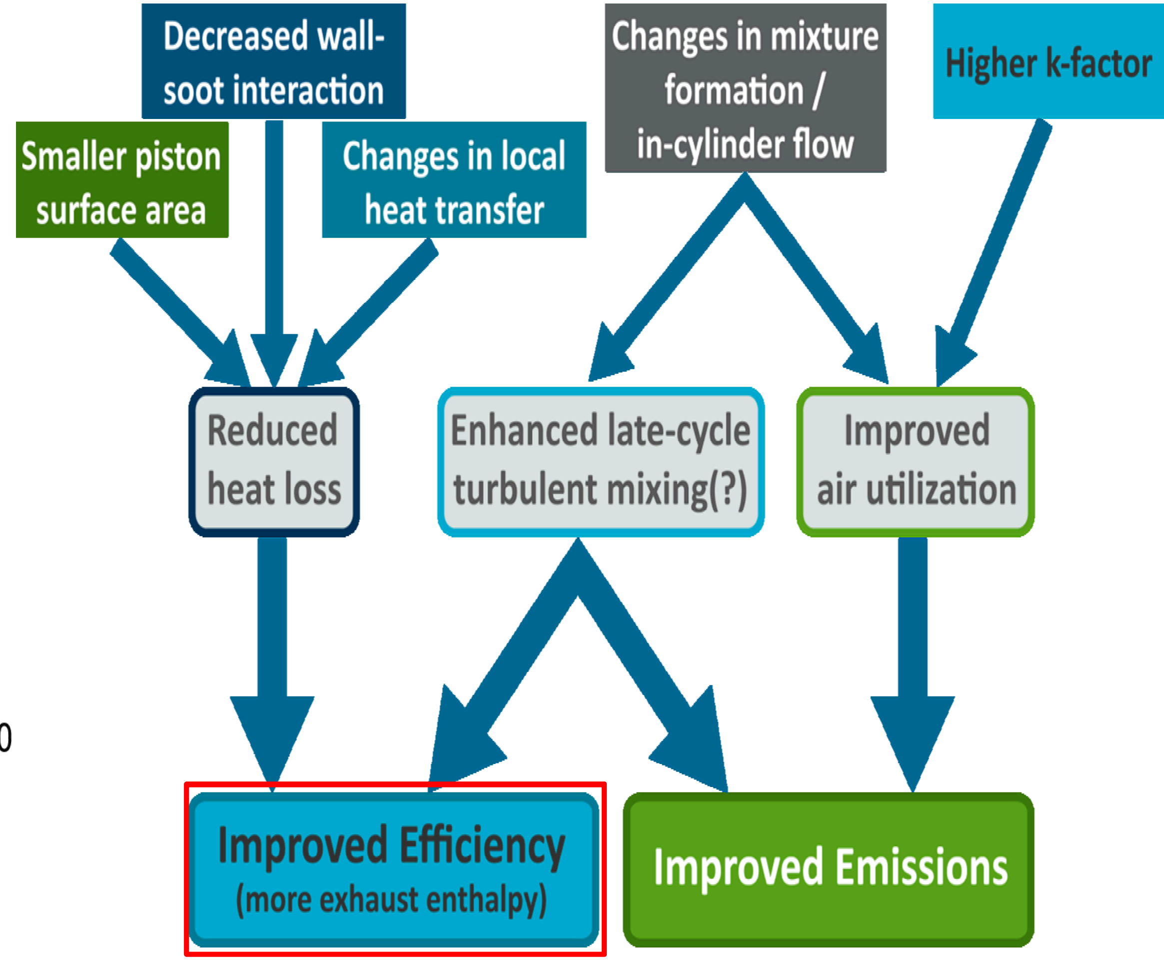




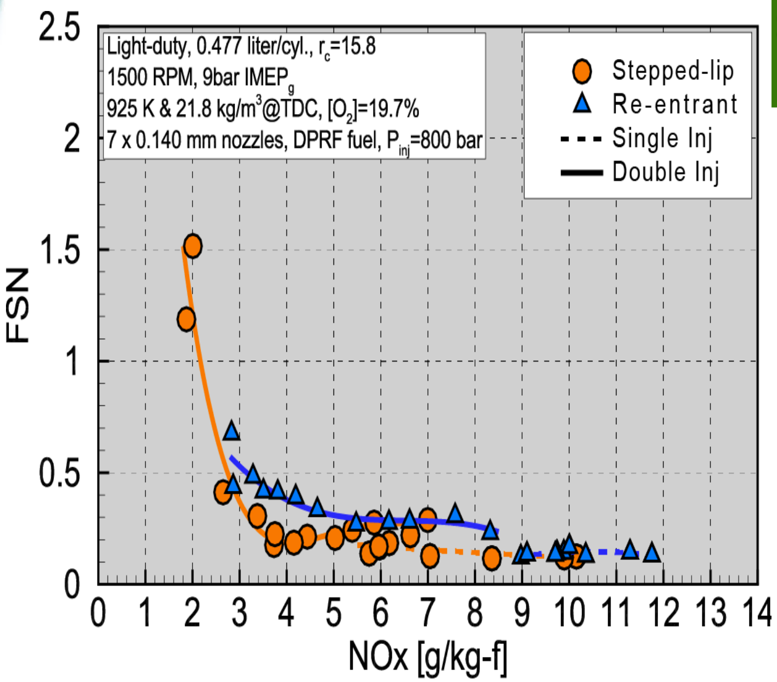
* Kurtz, E. and Styron, J., "An Assessment of Two Piston Bowl Concepts in a Medium-Duty Diesel Engine," *SAE Int. J. Engines* 5(2):344-352, 2012, doi:10.4271/2012-01-0423.

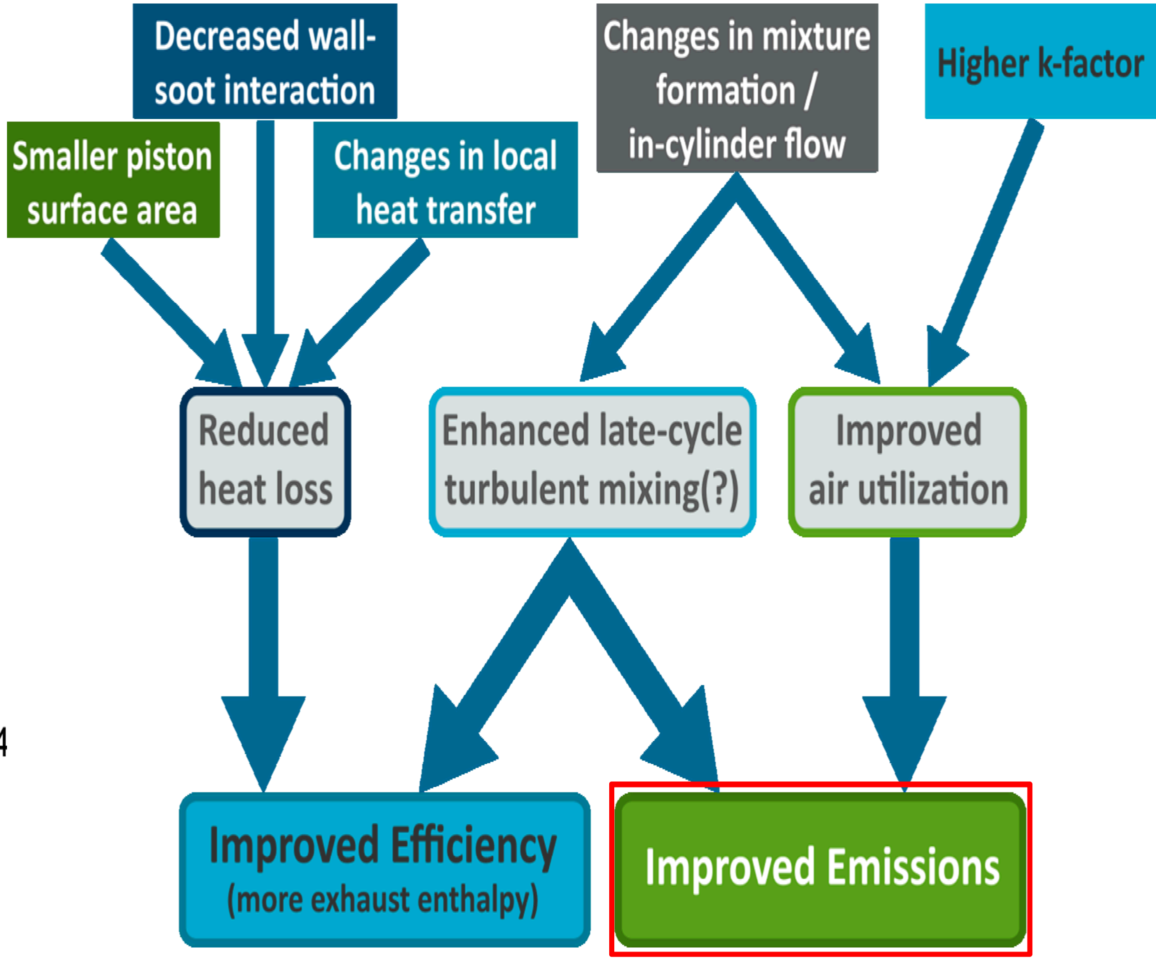
What makes the stepped-lip bowl more fuel efficient than the conventional bowl under medium load, conventional combustion regime?



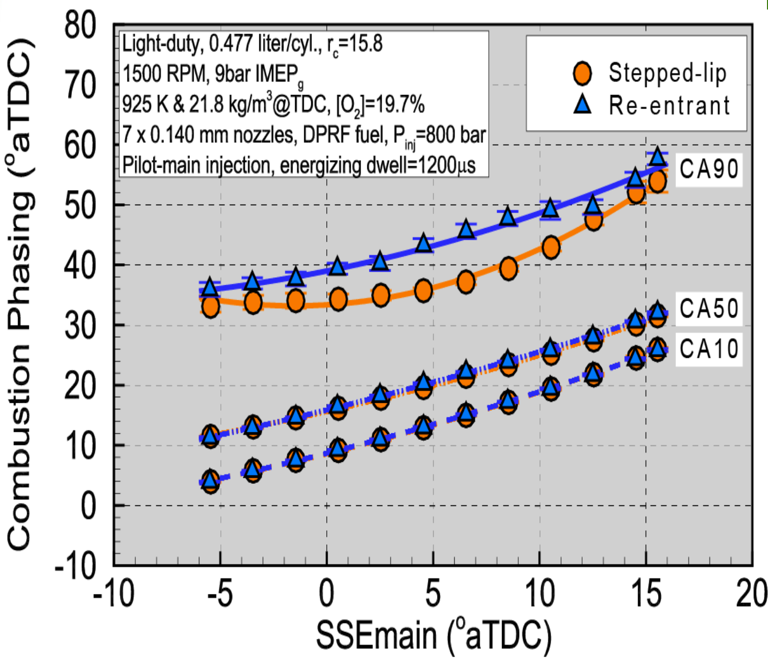


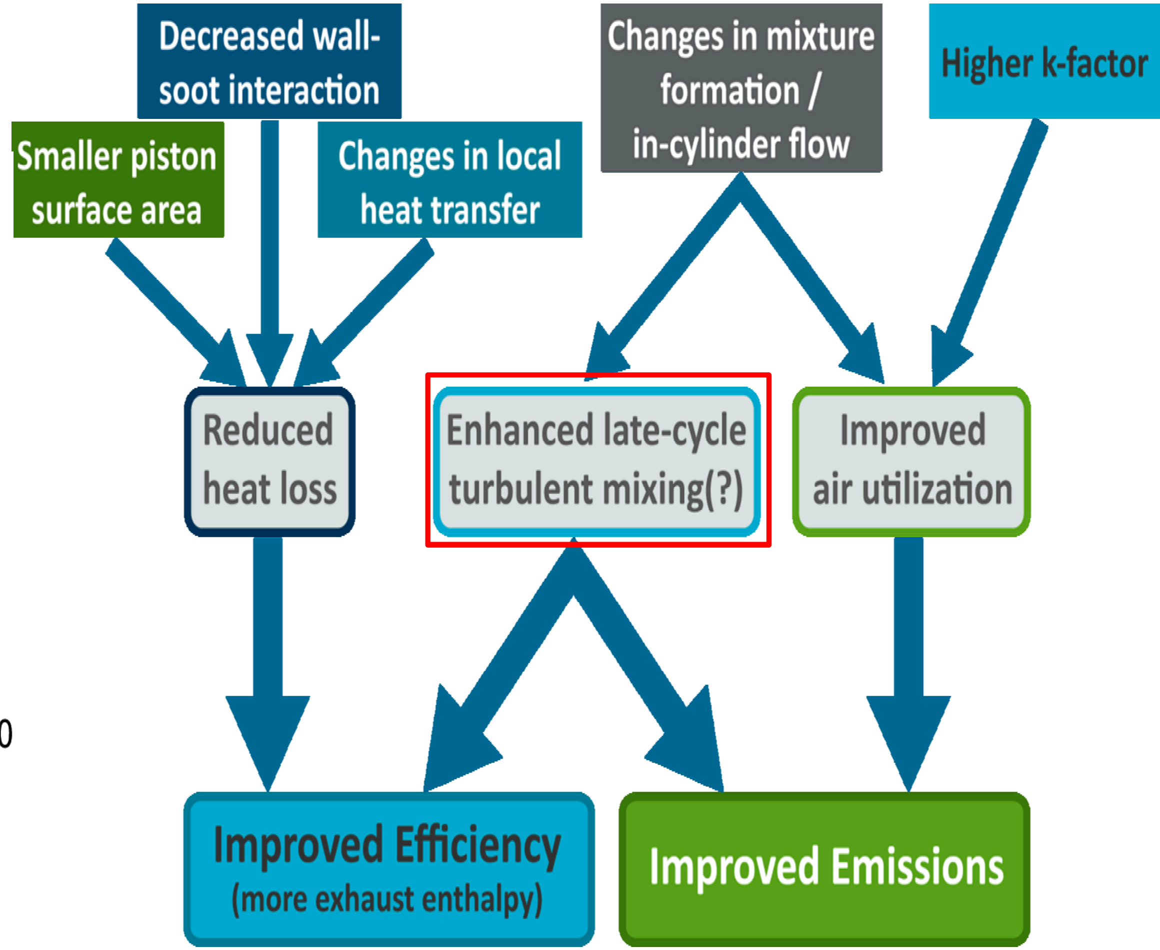
What makes the stepped-lip bowl resulting in a better soot-NOx trade-off than the conventional bowl under medium load, conventional combustion regime?



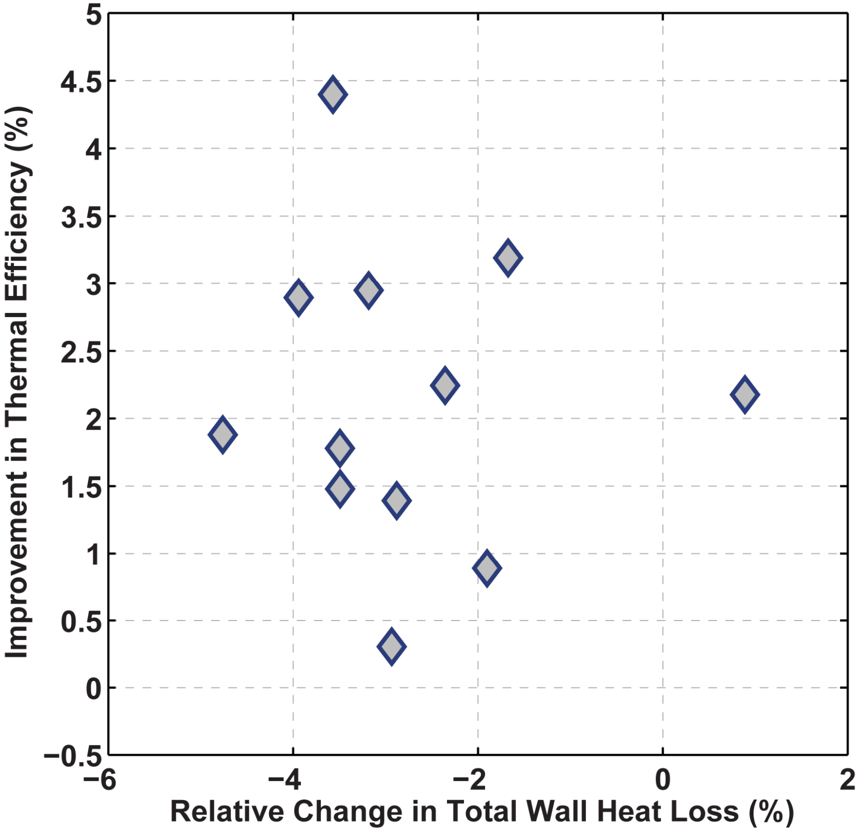


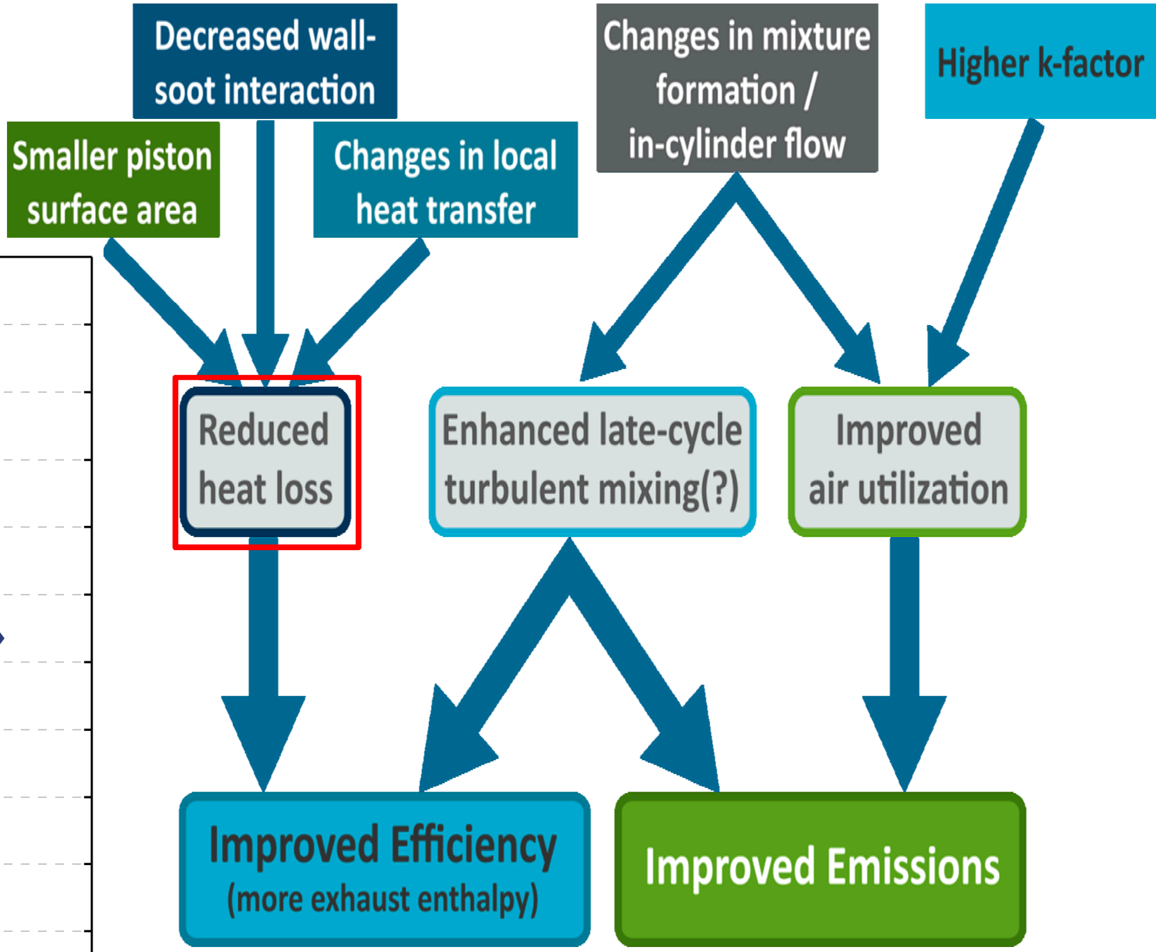
Metallic engine testing: fuel conversion efficiency improvements with the stepped-lip piston are most closely related to enhanced late-cycle heat release rates.



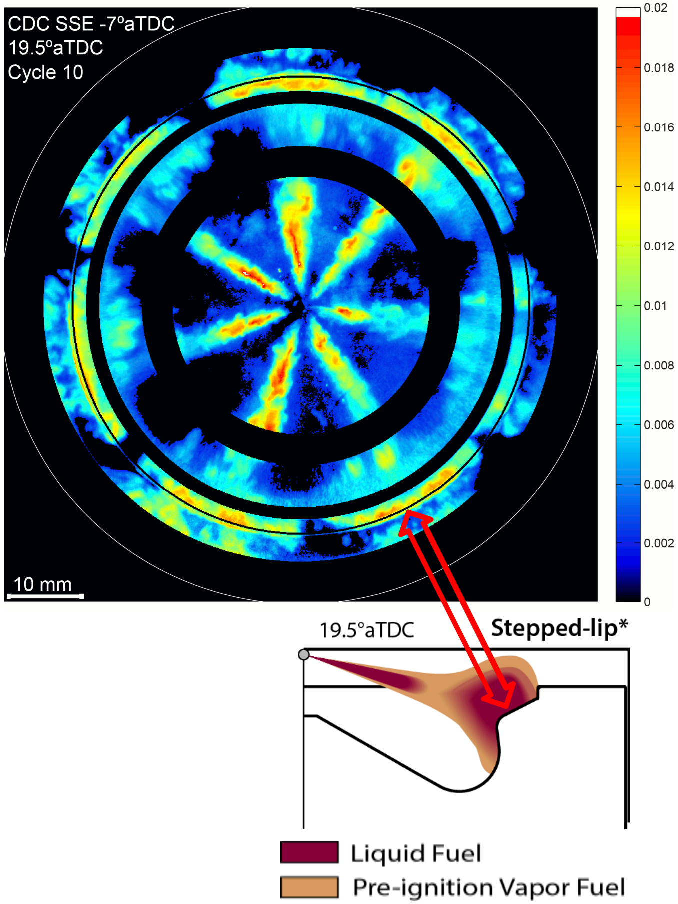


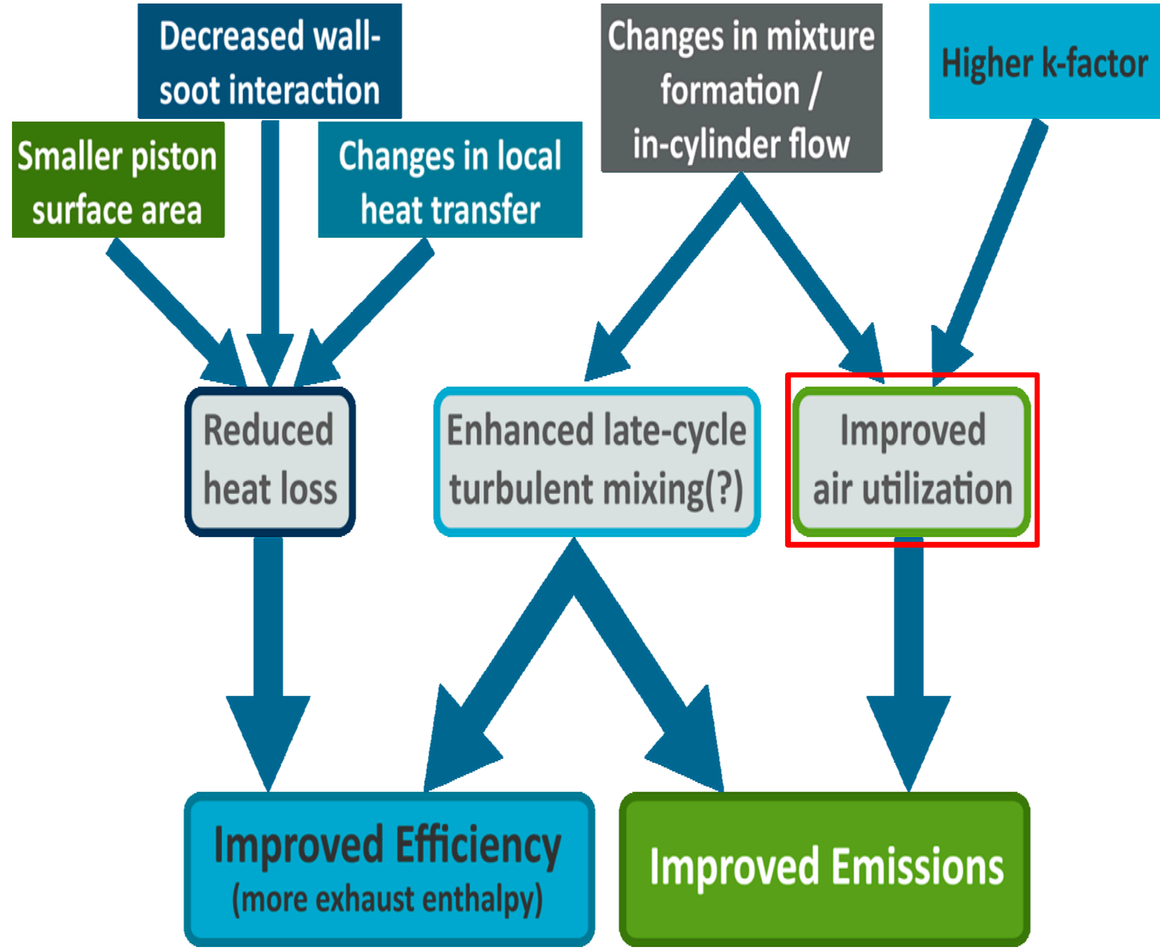
Thermodynamics analysis: wall heat losses are likely decreased with the stepped-lip piston, but these decreases are not well correlated with efficiency improvements.





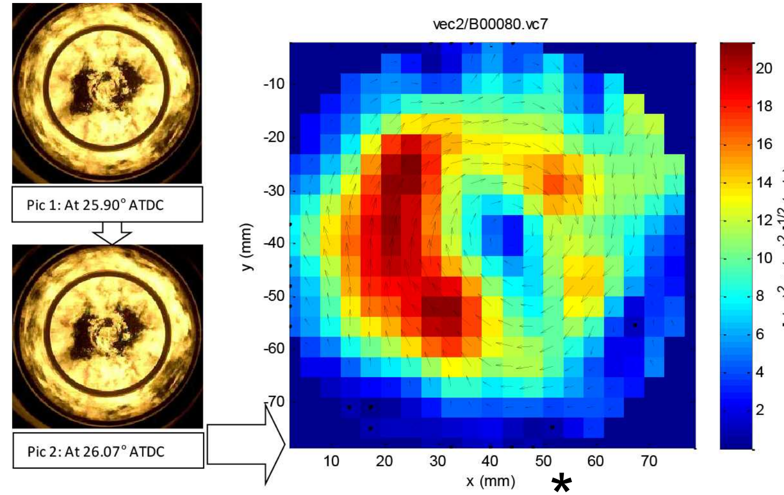
Fuel tracer PLIF observation: stepped-lip geometry results in localized high fuel concentration on lip shoulder, which implies better air utilization.





A non-intrusive in-situ in-cylinder diagnostic technique is needed to investigate late-stage combustion: Introduction to combustion image velocimetry (CIV).

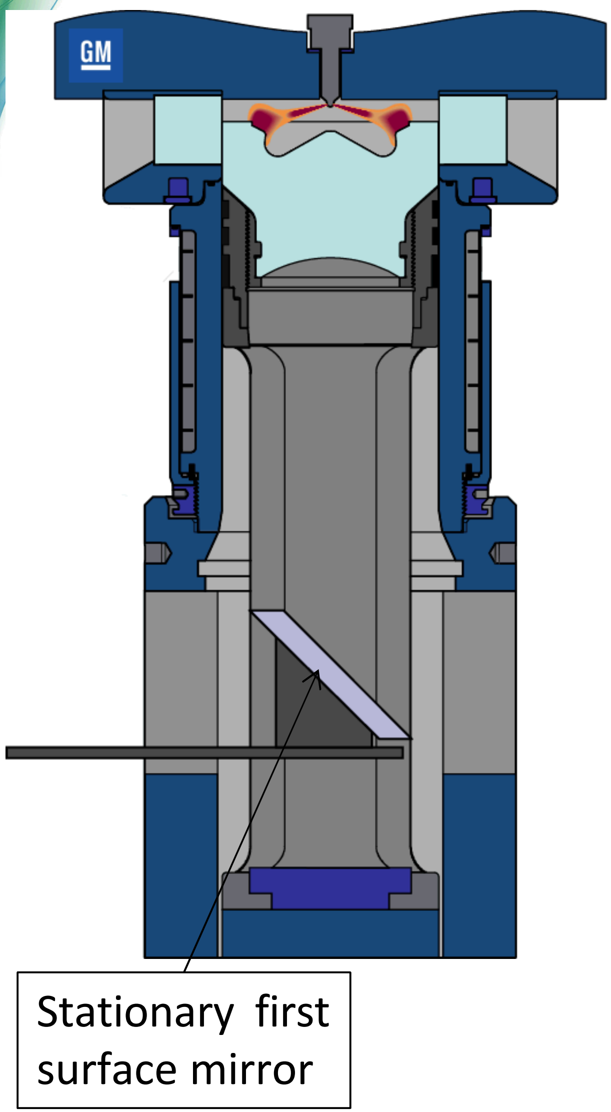
- Soot natural luminosity is sampled at high speed.
- Sampled soot radiation is used as tracking source.
- Frames are divided into interrogation windows and cross-correlated to calculate the velocity field.

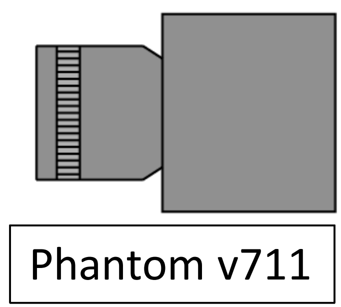


	PLIF / PIV	Combustion Image Velocimetry
[redacted]		
High-speed sampling		
[redacted]		
Easy interpretation	 (planar)	 (line-of-sight)

* Henrik W. R. Dembinski, "In-cylinder Flow Characterisation of Heavy Duty Diesel Engines Using Combustion Image Velocimetry," *Ph.D. thesis*, 2013.

High-speed soot natural luminosity imaging setup



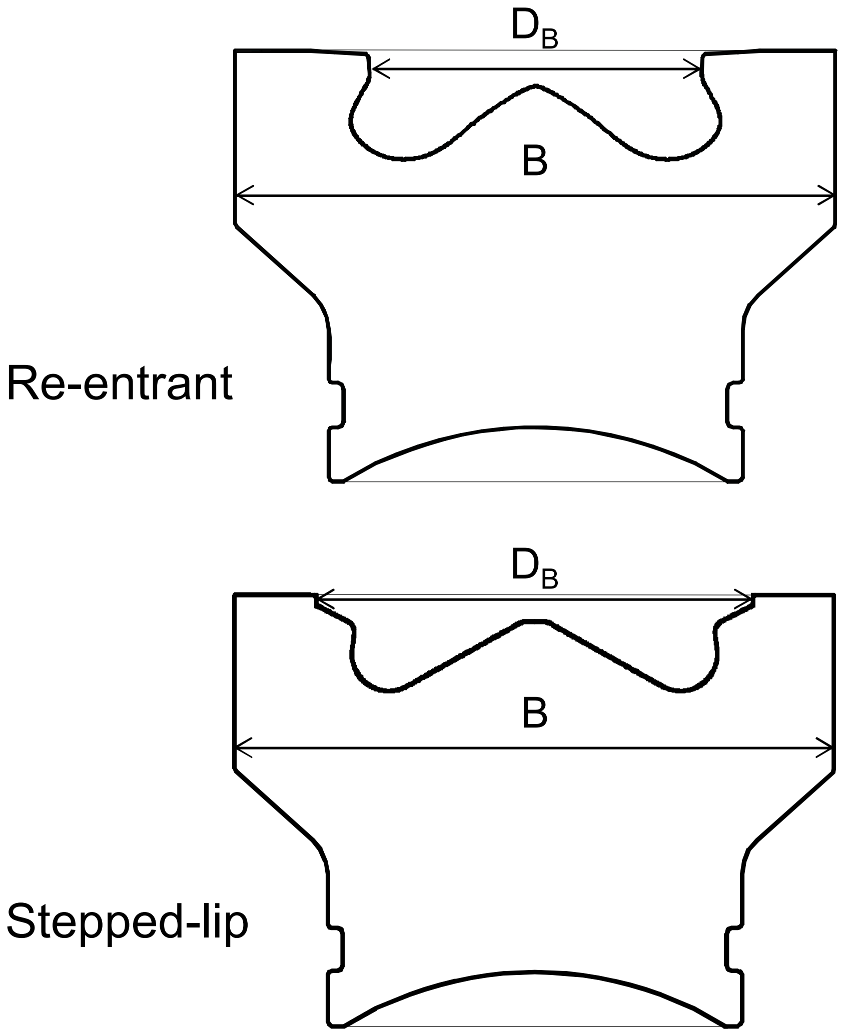


Research engine	Single-cylinder
Cycle	4-stroke
Intake/Exhaust Valves	2/2
Bore x Stroke	82 x 90.4 mm
Displacement per cylinder	0.477 liters
Compression ratio	15.8
Squish height	1.35 mm
Bowl-to-bore ratio	0.55/0.73

- Engine operation
  - 1500 rpm
  - O_2 mole fraction: 19.7%
  - Fuel: 42 vol% n-hexadecane + 58 vol% heptamethylnonane
  - Swirl ratio: 2.2
- Imaging
  - Monochromatic CMOS camera (Phantom v711)
  - Frame rate: 40 kHz
  - Exposure time: 2.5μs

SNL optical piston bowl geometries

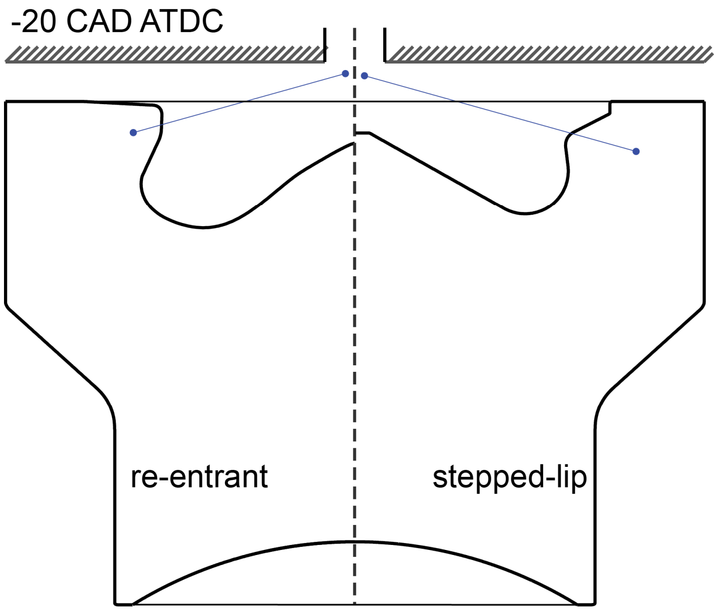
- Two quartz pistons have identical:
  - Bowl volume = 0.028 L
  - Squish height = 1.35 mm
  - Compression ratio = 15.8
  - No valve cut-outs
- Different bowl geometry result in different bowl-to-bore ratio:
  - Re-entrant: $D_B/B=0.55$
  - Stepped-lip: $D_B/B=0.73$
- Surface area of stepped-lip bowl is ~10% less than for the conventional bowl
- Injector tip penetration is set based on recommendations from OEM partners



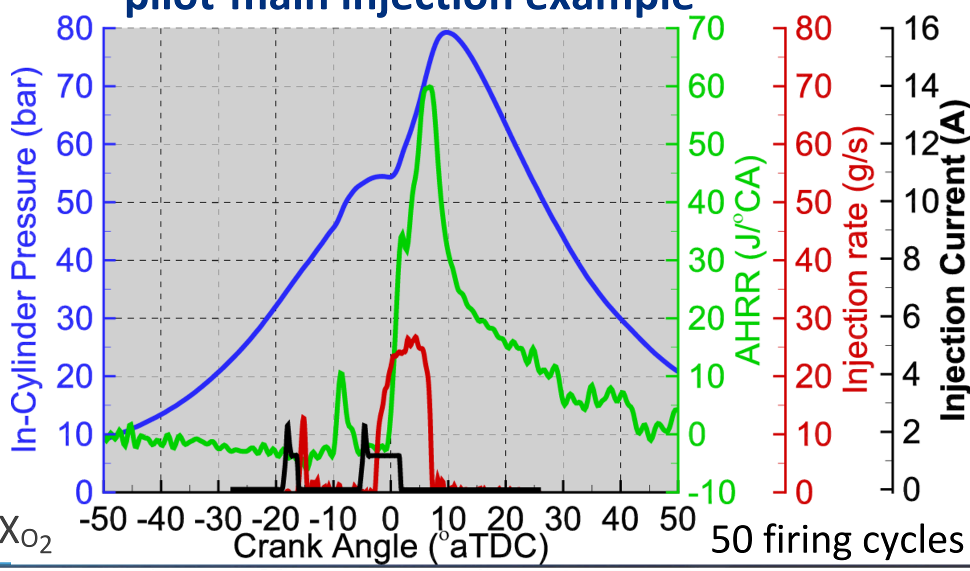
Conventional operating conditions

Engine speed	1500 rpm
Intake charge mole fractions	O_2 : 19.7% CO_2: 1.1% N_2 : 79.2%
Constant intake mass flow rate	8.936 g/s
Intake temperature	80 ^oC
Intake pressure	~ 1.5 bar
$IMEP_g$	9.0 bar
Injected fuel (Pilot/Main)	1.4 / ~ 25 mg/str
Injection pressure	800 bar
$SSE_{(pilot)}$ sweep timings	-17,-7,2 CAD^{o}aTDC
Energizing dwell	1200 μs
Main inj. duration	~6.5 CAD
Swirl ratio (Ricardo)	2.2
TDC density	21.8 kg/m^3
TDC temperature	925 K

- 0^oCA are referenced to the firing TDC
- Engine is skip-fired: 1 fired + 4 motored
- N_2 and CO_2 added to intake air to achieve target X_{O_2}



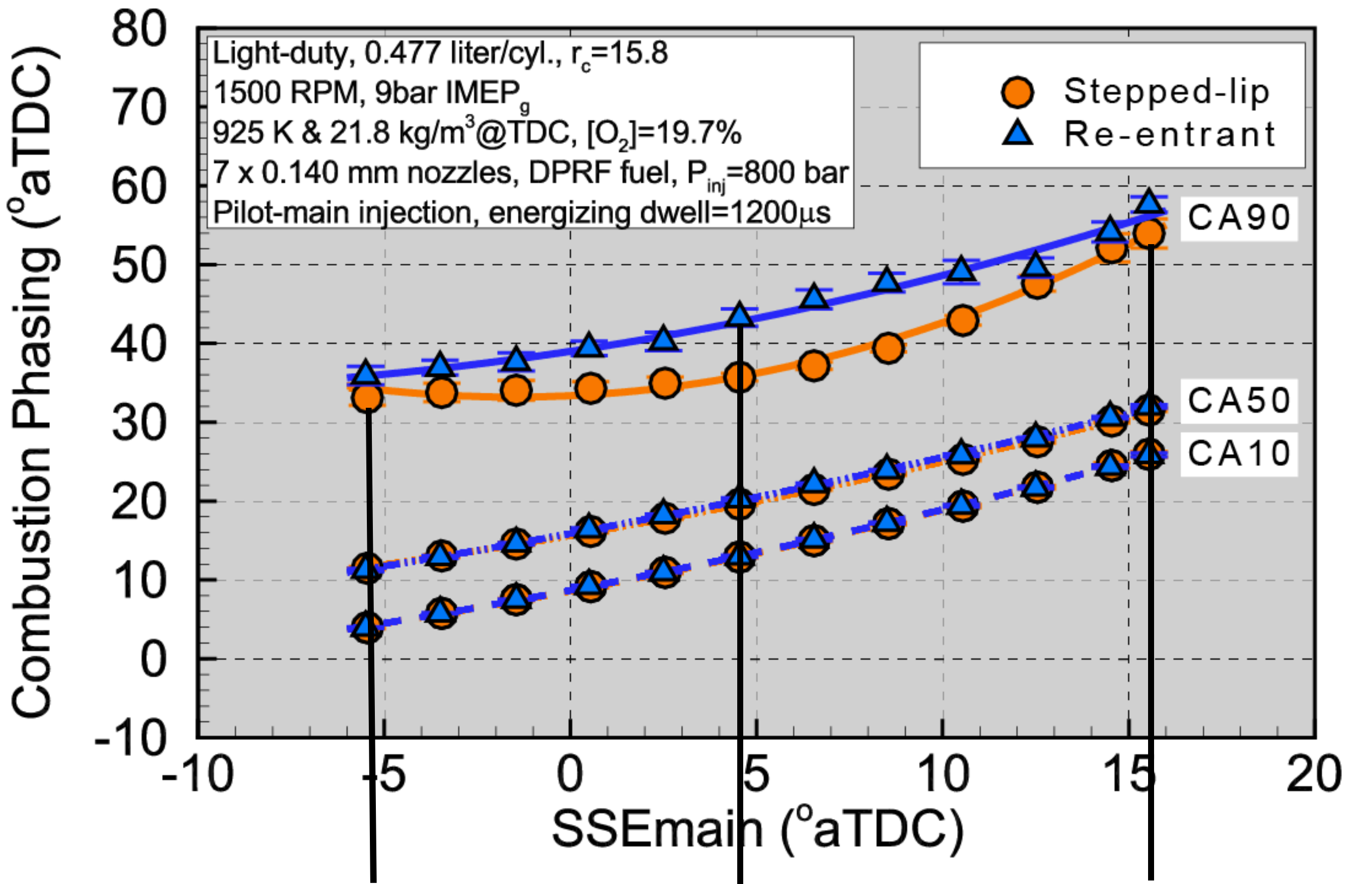
pilot-main injection example



50 firing cycles

Test Matrix

Double-injection, conventional combustion

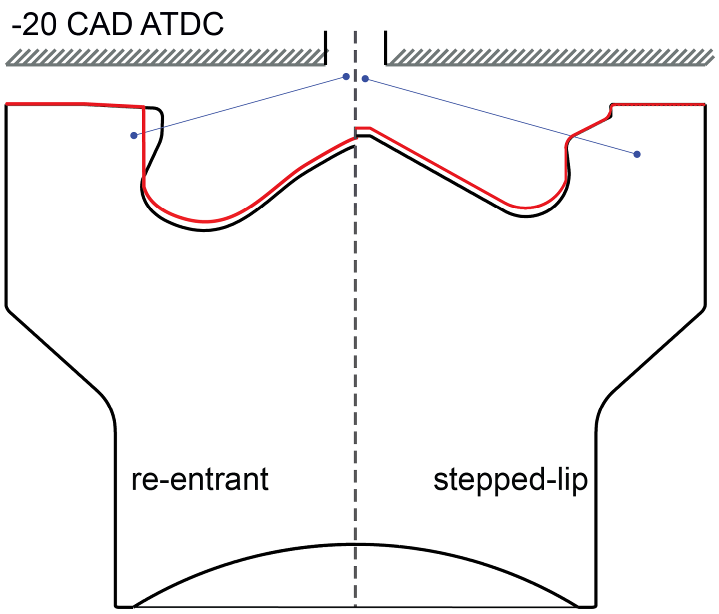


SSE_{pilot}=-17°aTDC

SSE_{pilot}=-7°aTDC

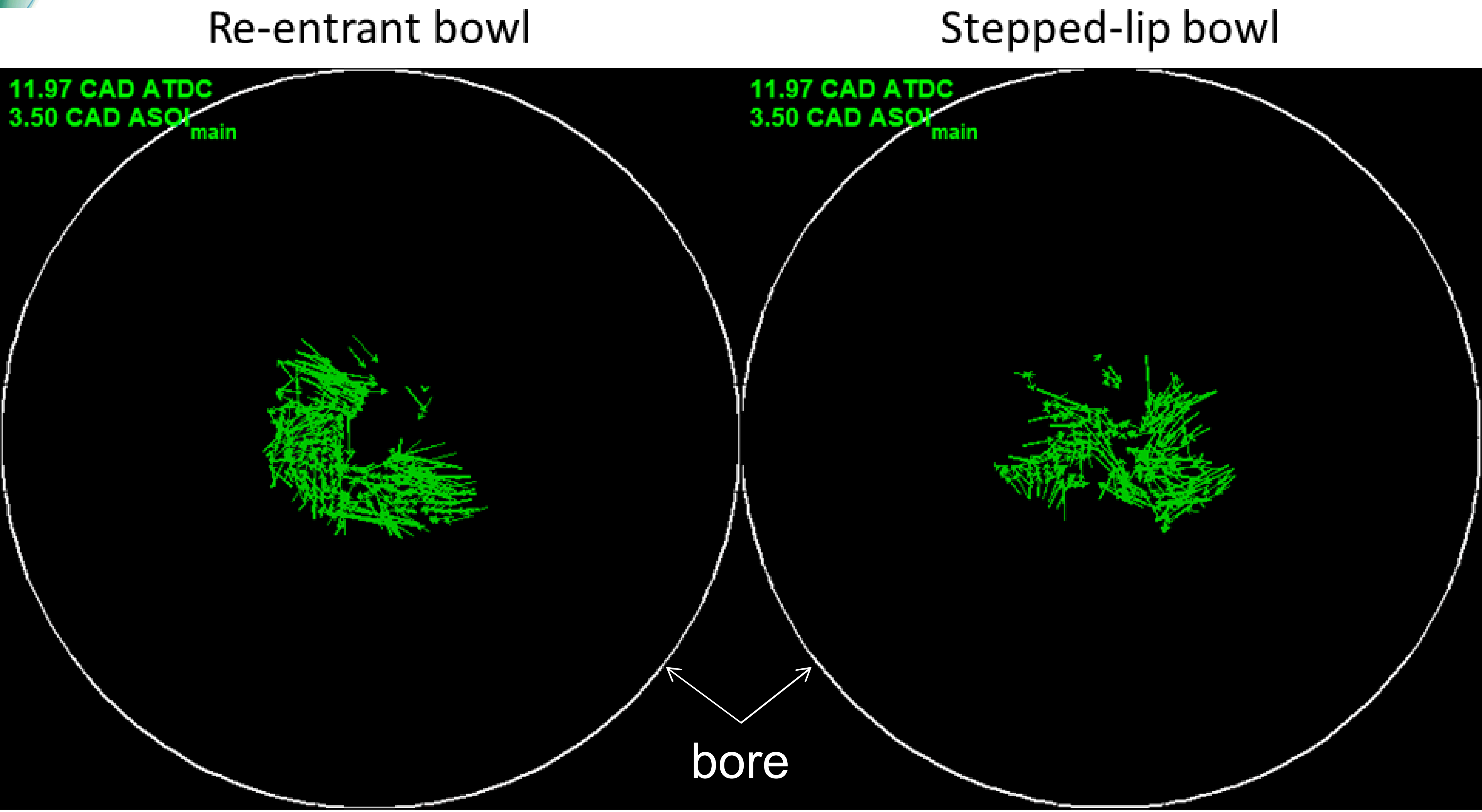
SSE_{pilot}=2°aTDC

Image Processing



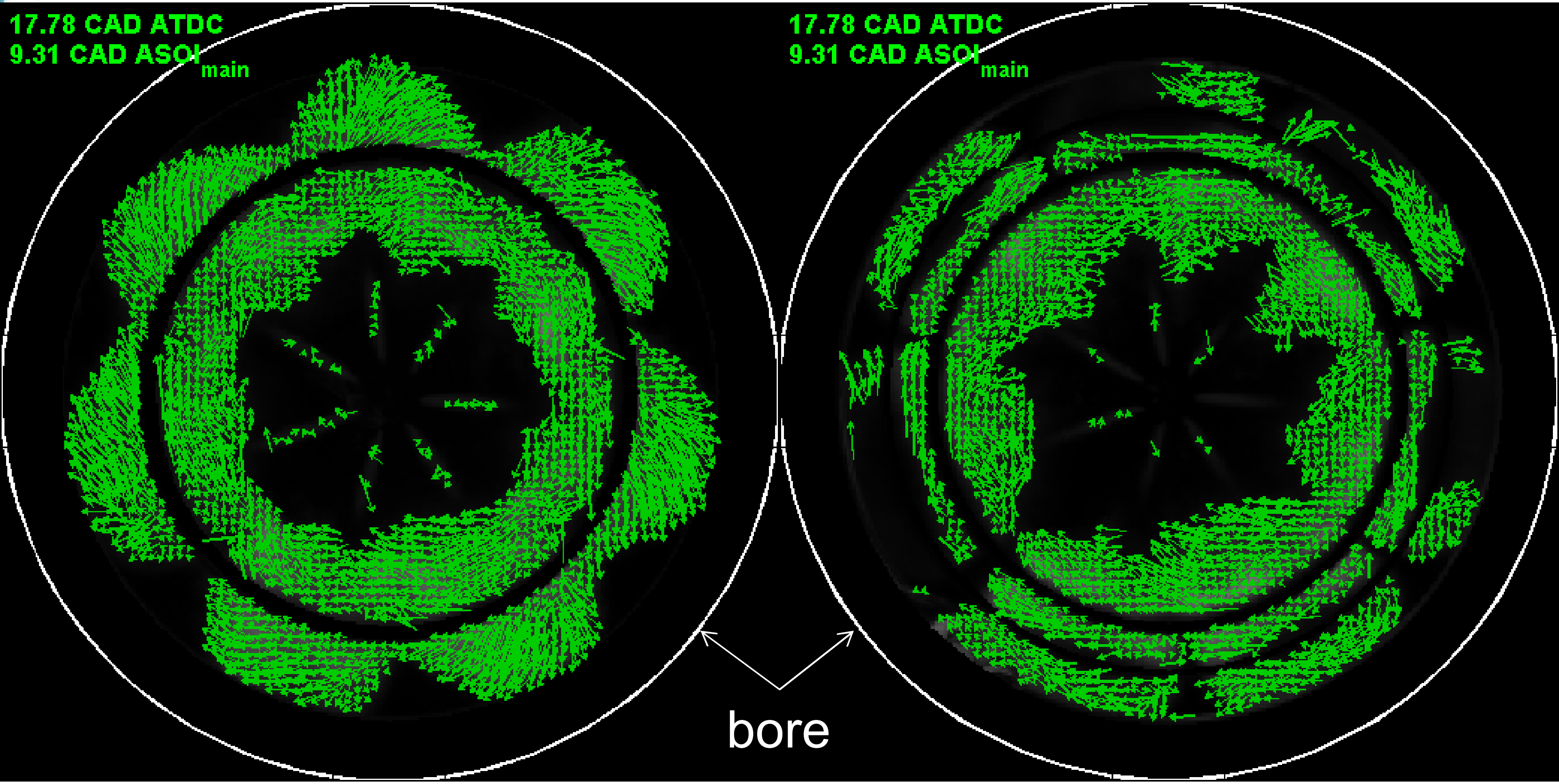
- Optical distortion correction is performed assuming sampled soot luminosity originates from the piston surface (red):
  - Bowl region: 1 mm above the piston surface.
  - Rest of area: 0.1 mm above the piston surface.
- This assumption may induce radial location errors in dewarped images.
- Spatially-variant image resolution brought by the curved dewarping surface is quantified.
- Change in image resolution due to piston position is accounted for every CAD.
- LaVision PIV software DaVis is used to perform cross-correlation.

Comparison of CIV-resolved ensemble-averaged velocity fields between two piston geometries, SSE_{pilot}=-7°aTDC.

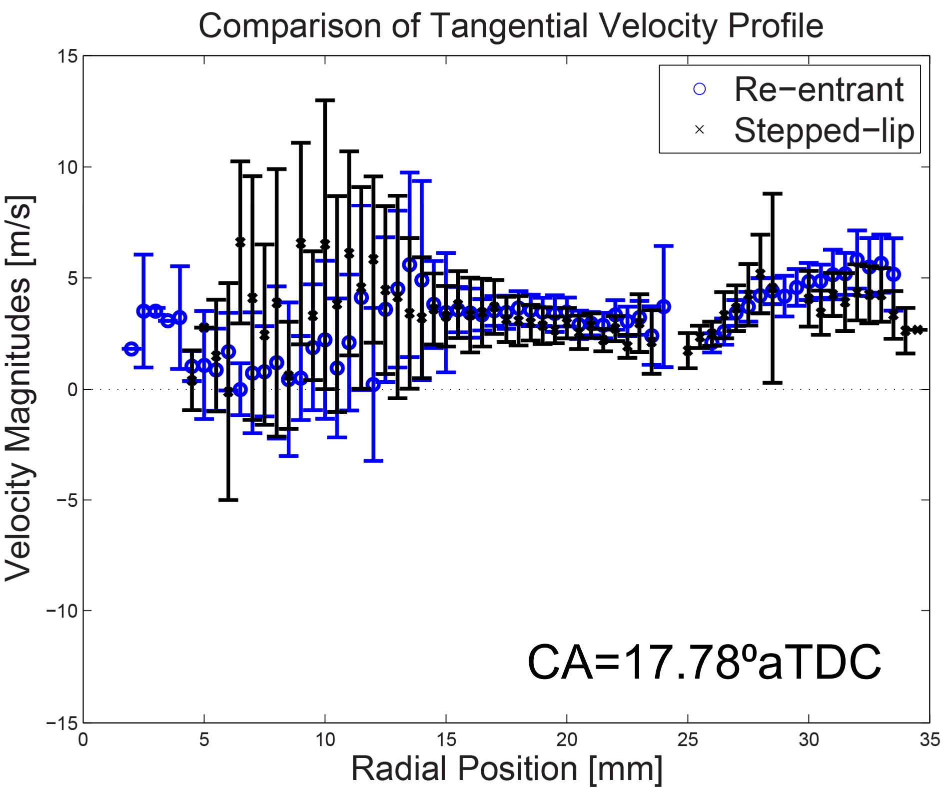


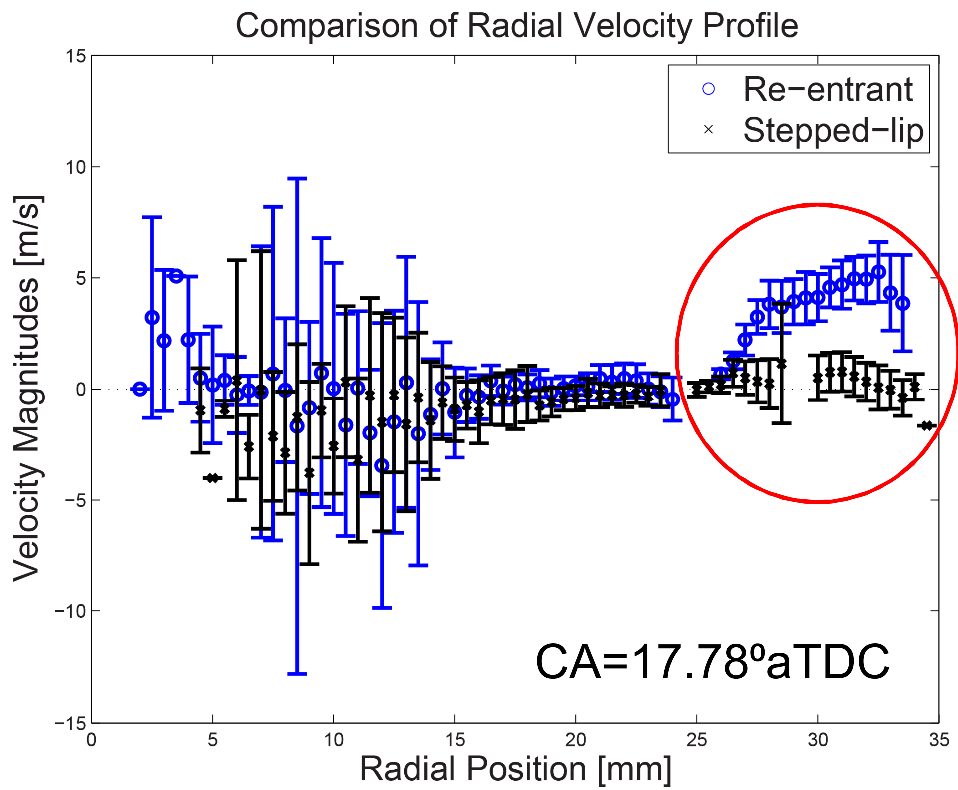
Although early-stage of combustion phasing (CA10-CA50) is similar between two geometries, a different combustion-induced flow structure is observed with CIV.

Re-entrant bowl | Stepped-lip bowl



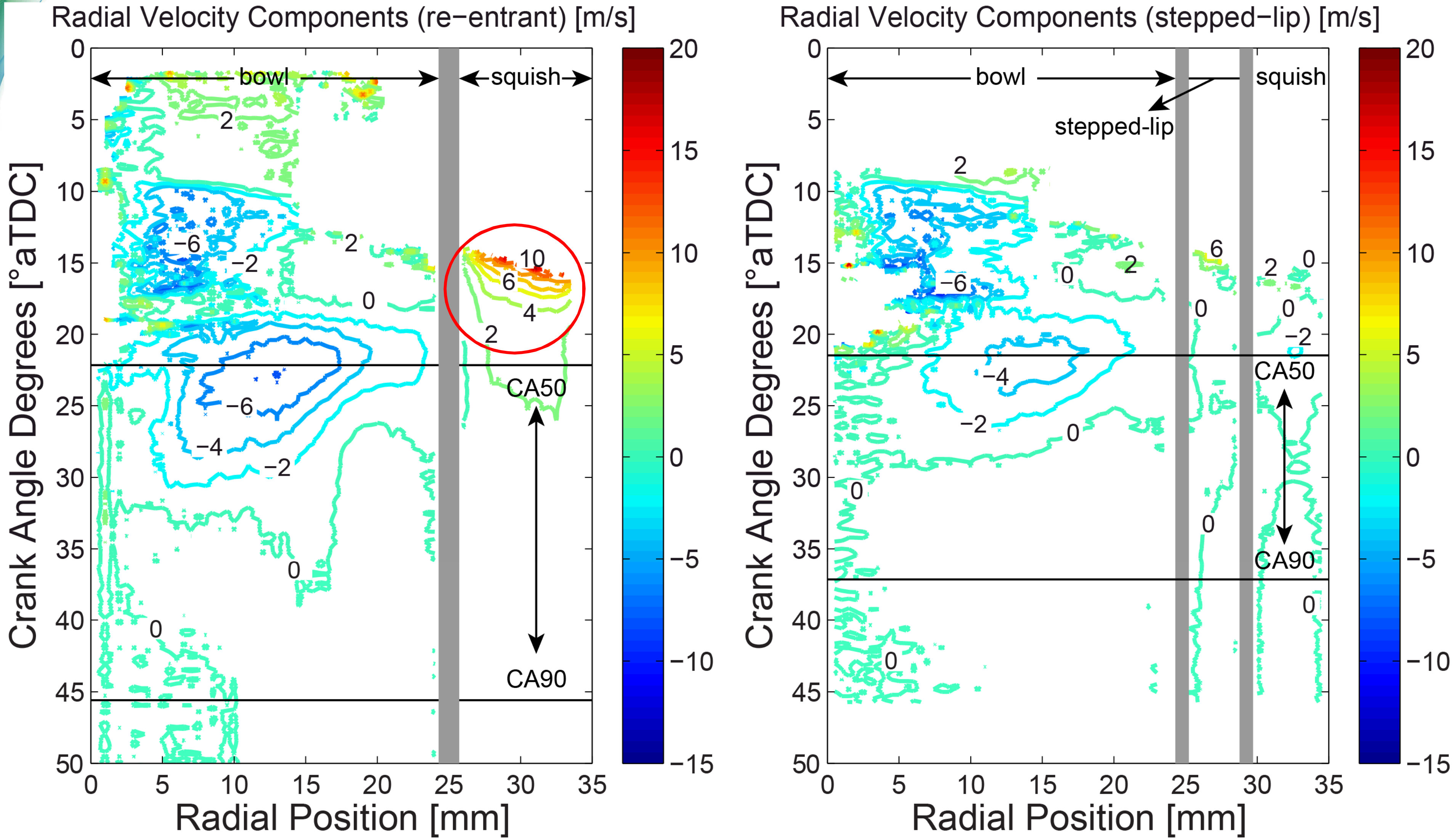
During the early-stage of combustion phasing (CA10-CA50), tangential velocity profile is similar between two geometries. However, re-entrant bowl exhibits larger outwards radial velocities in squish region.



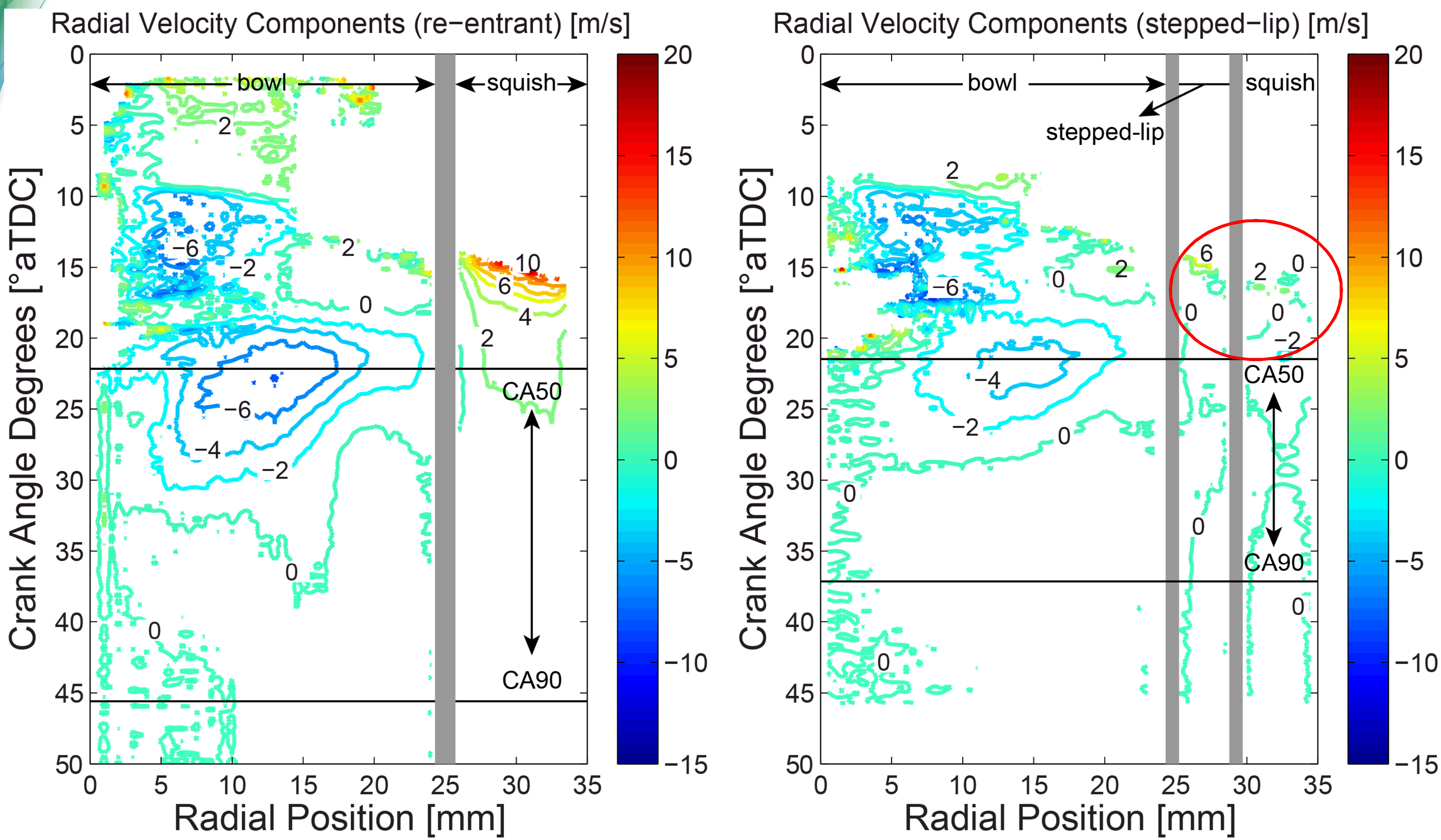


Error bar marks ±σ of velocity magnitudes away from 30-cycle ensemble-averaged value.

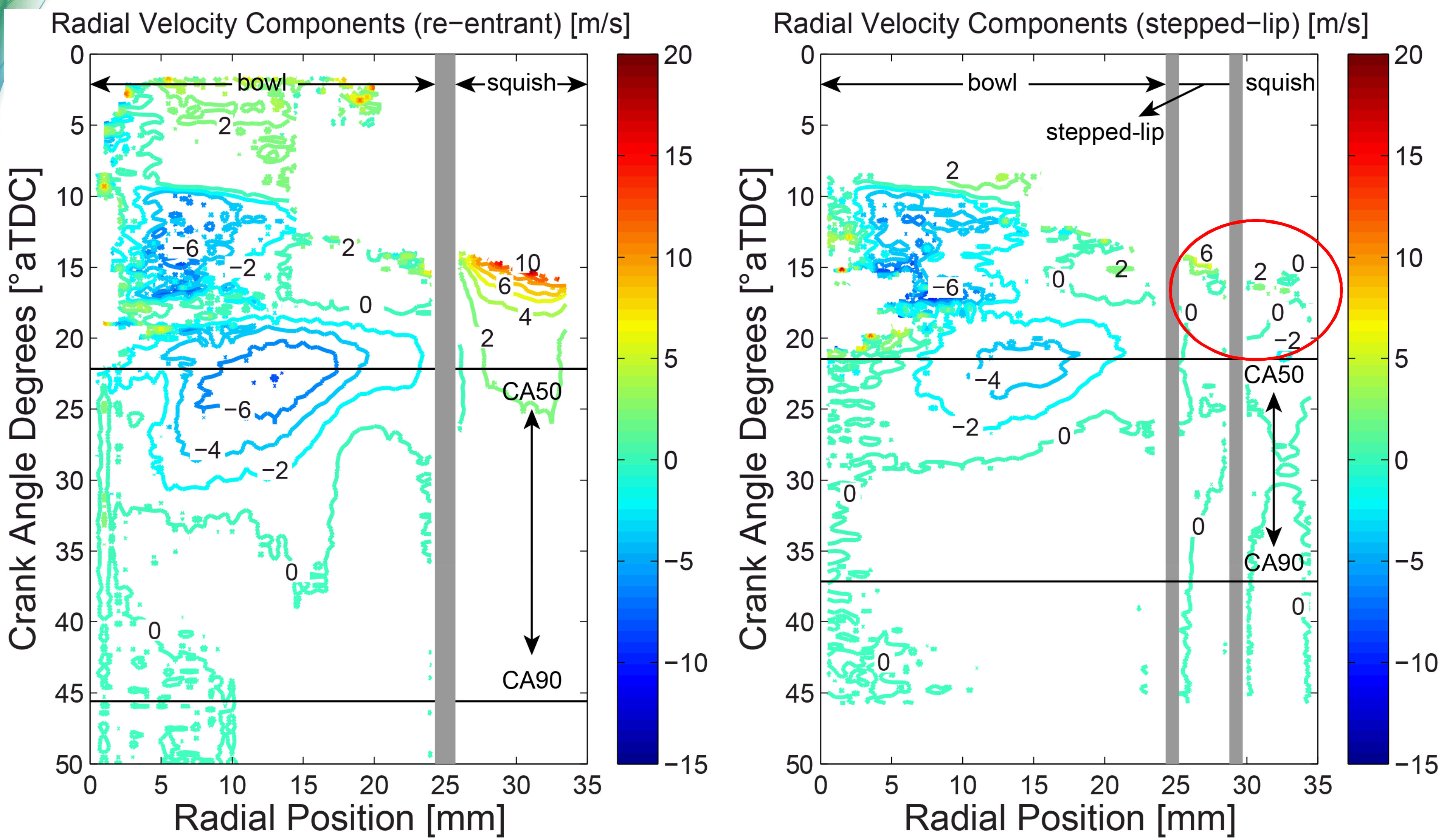
Soot clouds tend to penetrate radially into the squish region for re-entrant bowl (CA10-CA50).



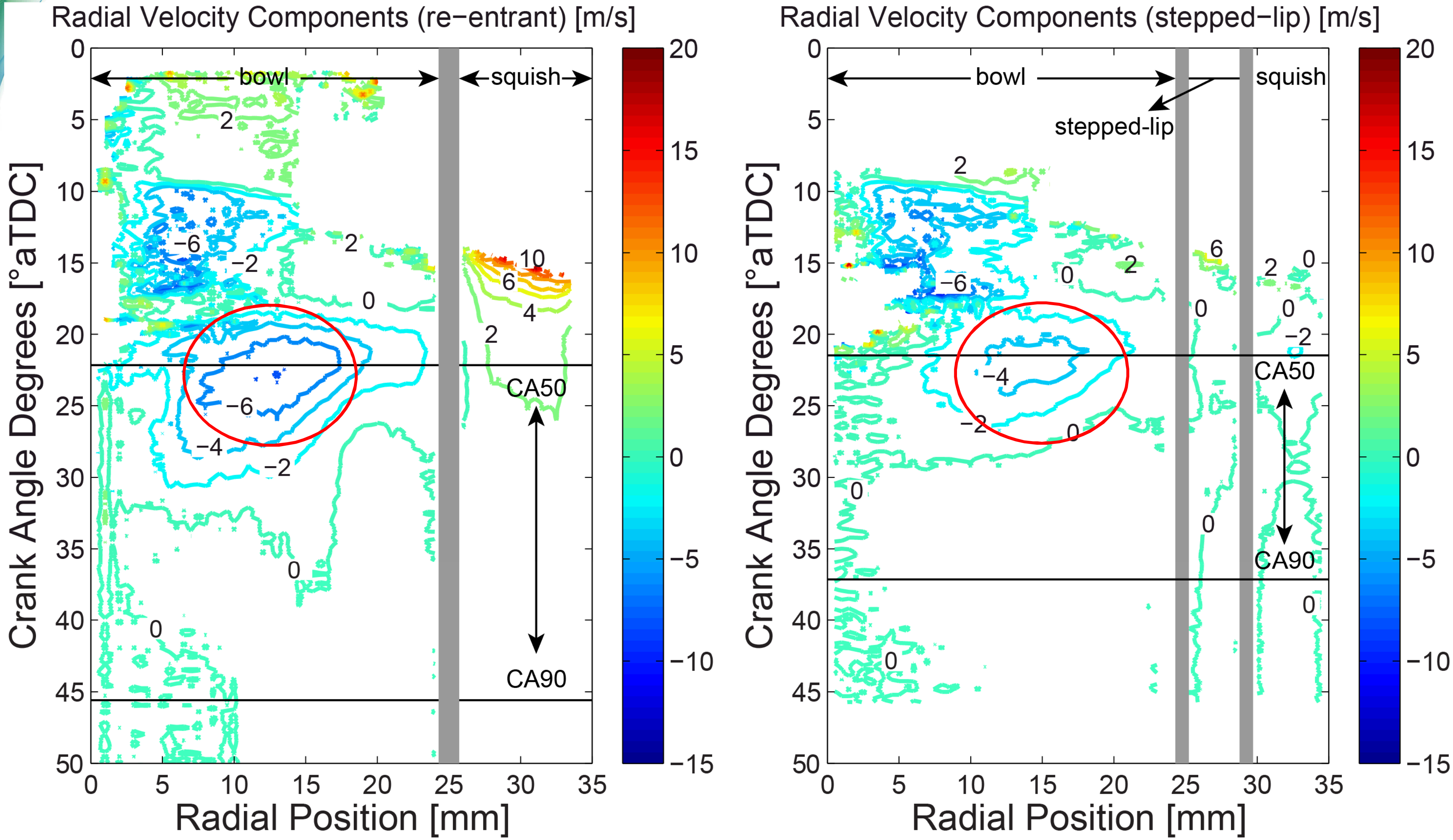
Soot clouds do not exhibit significant radial penetration into the squish region for stepped-lip bowl (CA10-CA50)



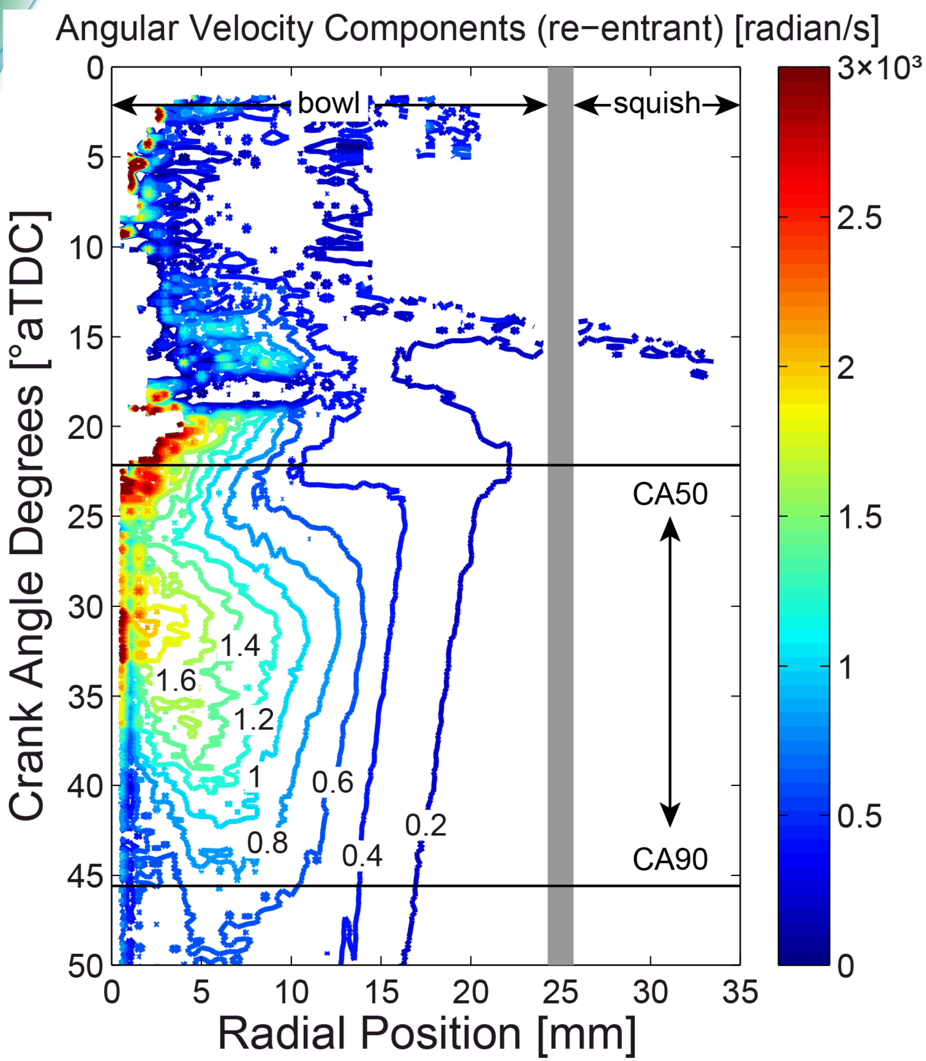
A slightly inwards radial velocities in squish zone imply local flow recirculation formed in stepped-lip region.

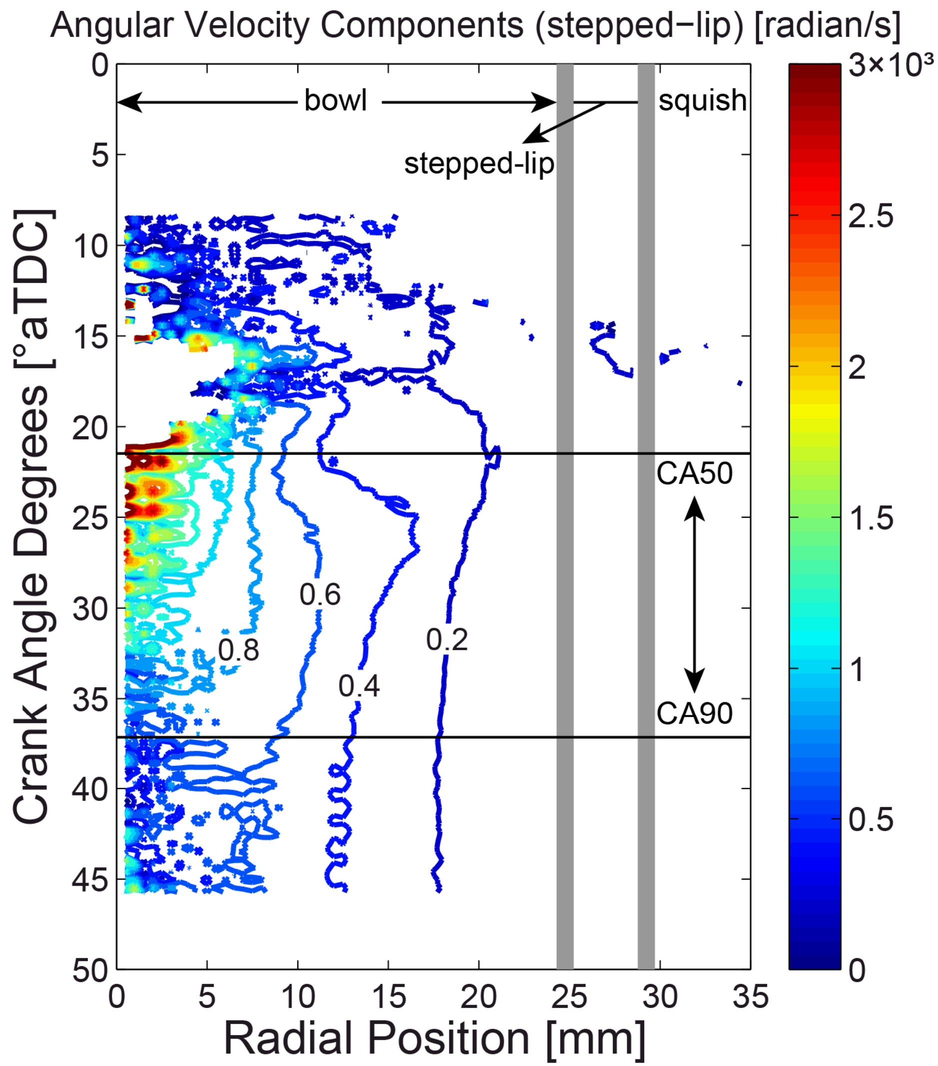


Bowl-region-soot clouds moving towards piston pip have been observed near CA50 for both piston geometries.

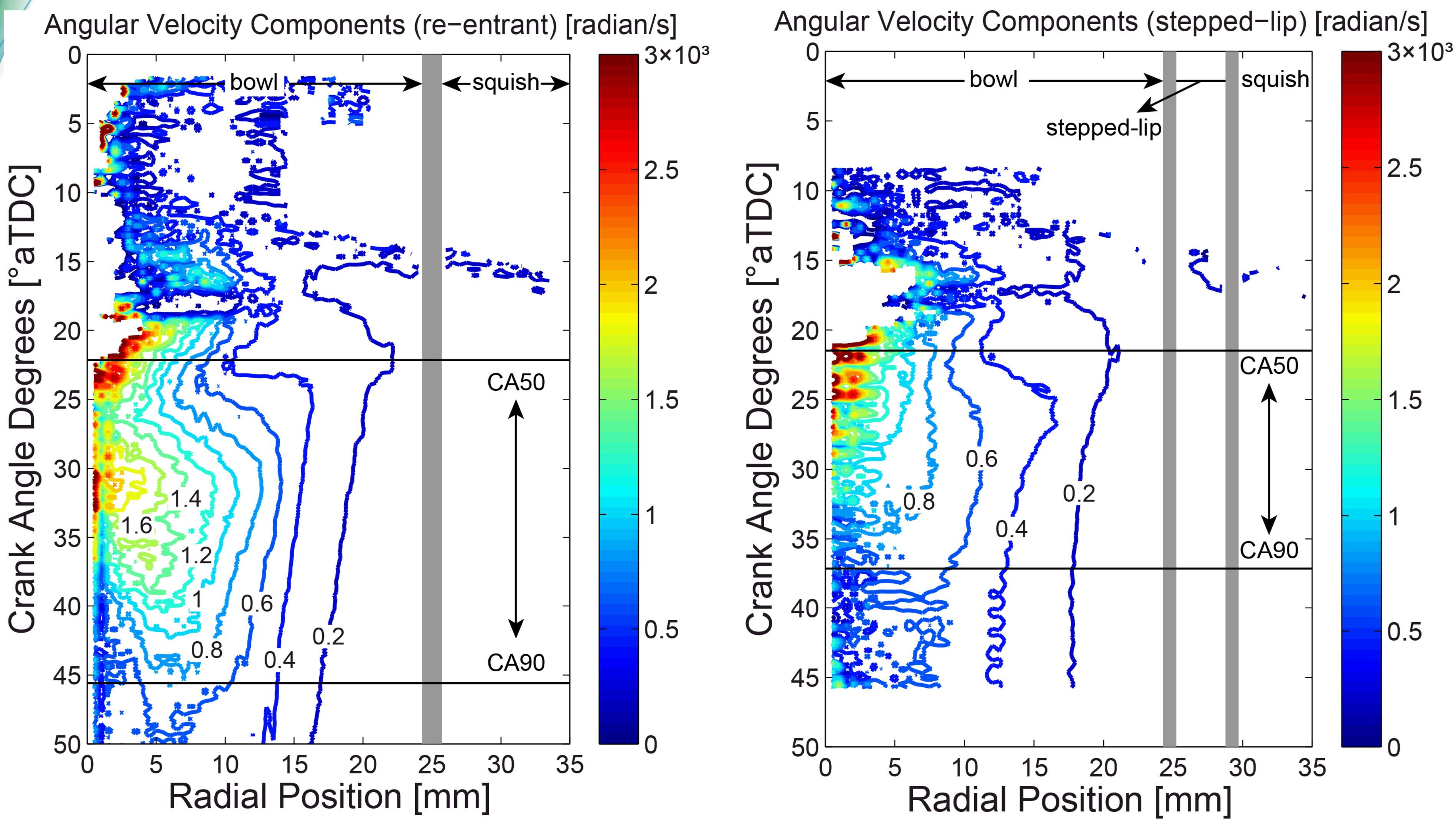


During late-stage combustion, angular velocity increases as the spray does work on the swirling in-cylinder charge, displacing it inward.

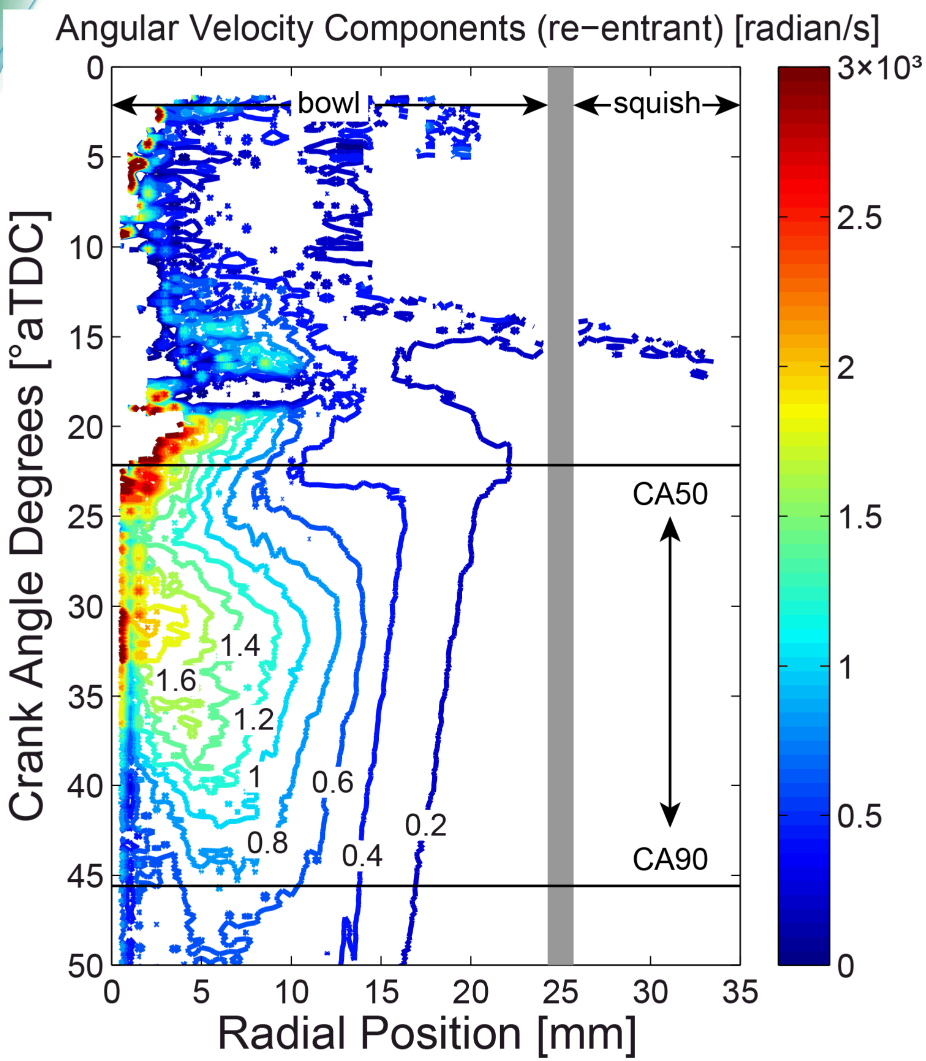


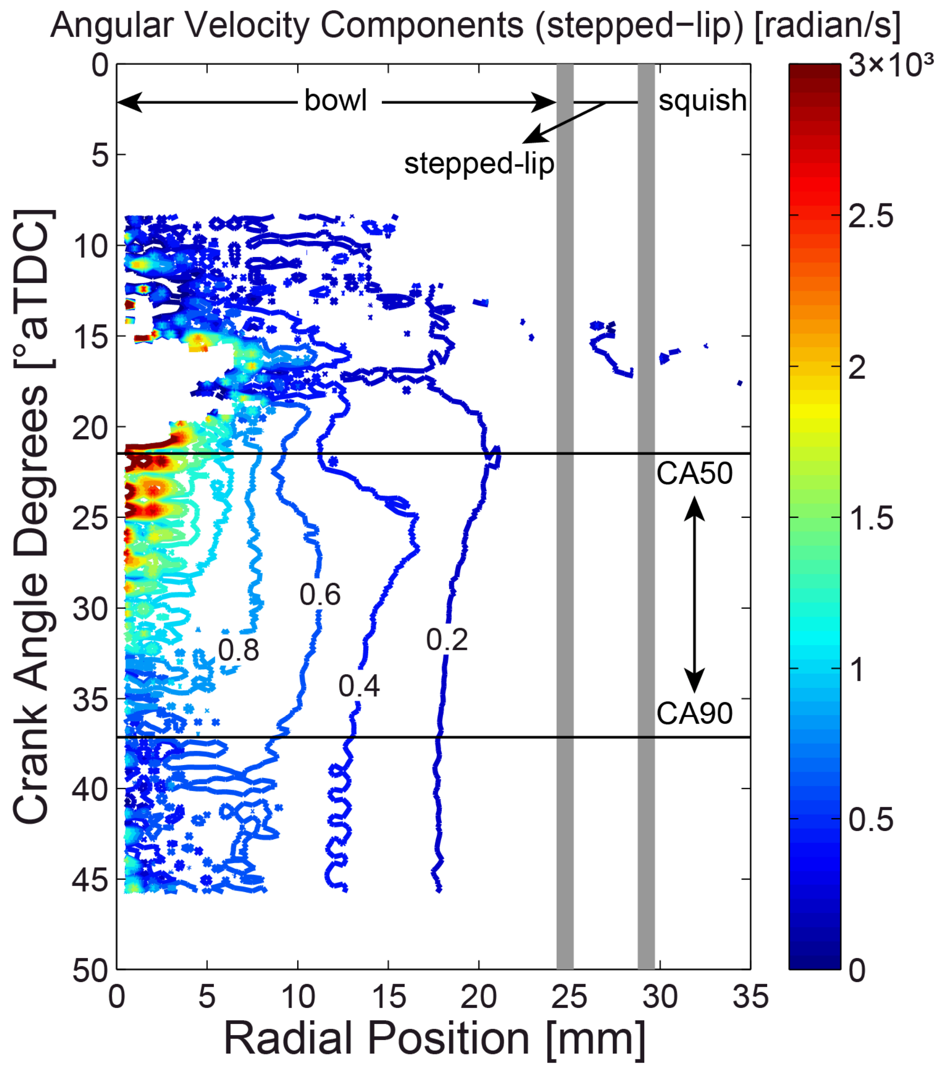


Angular velocity increase more for re-entrant bowl due to the deeper penetration of its low-angular-momentum sooty charge into the squish region.

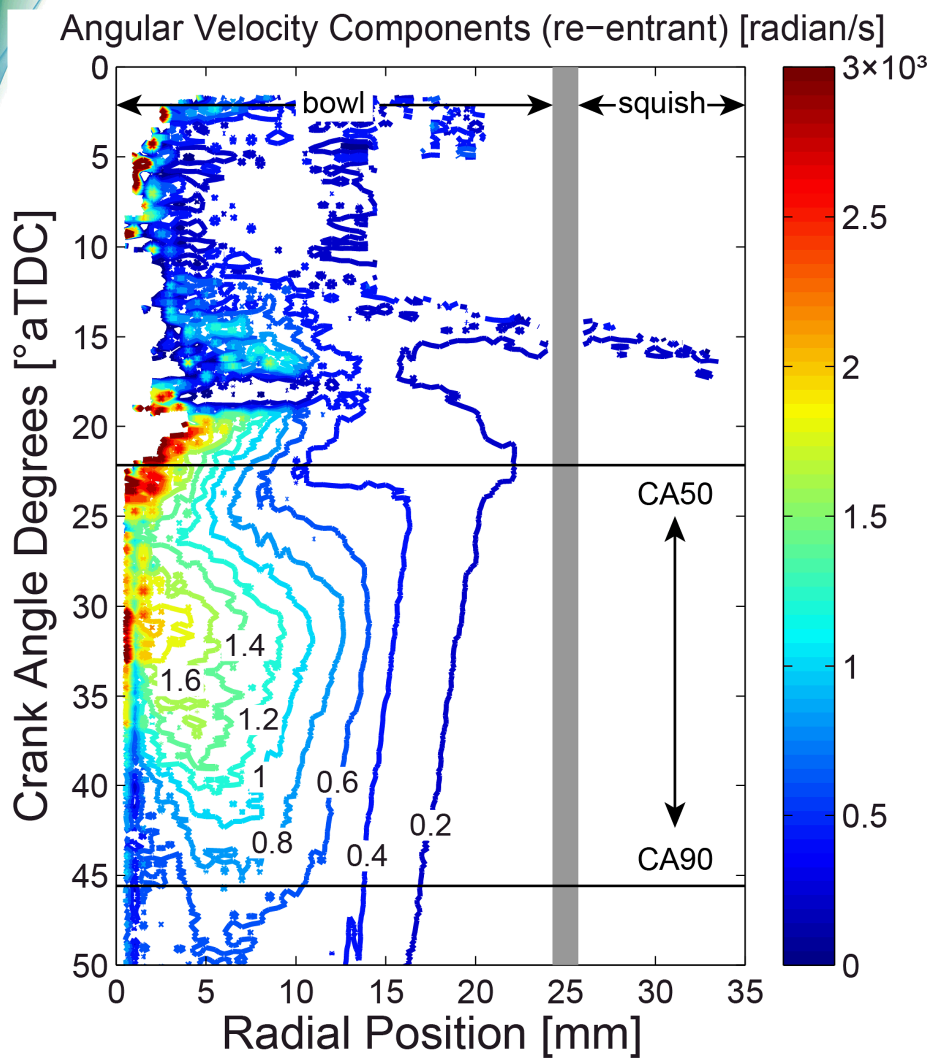


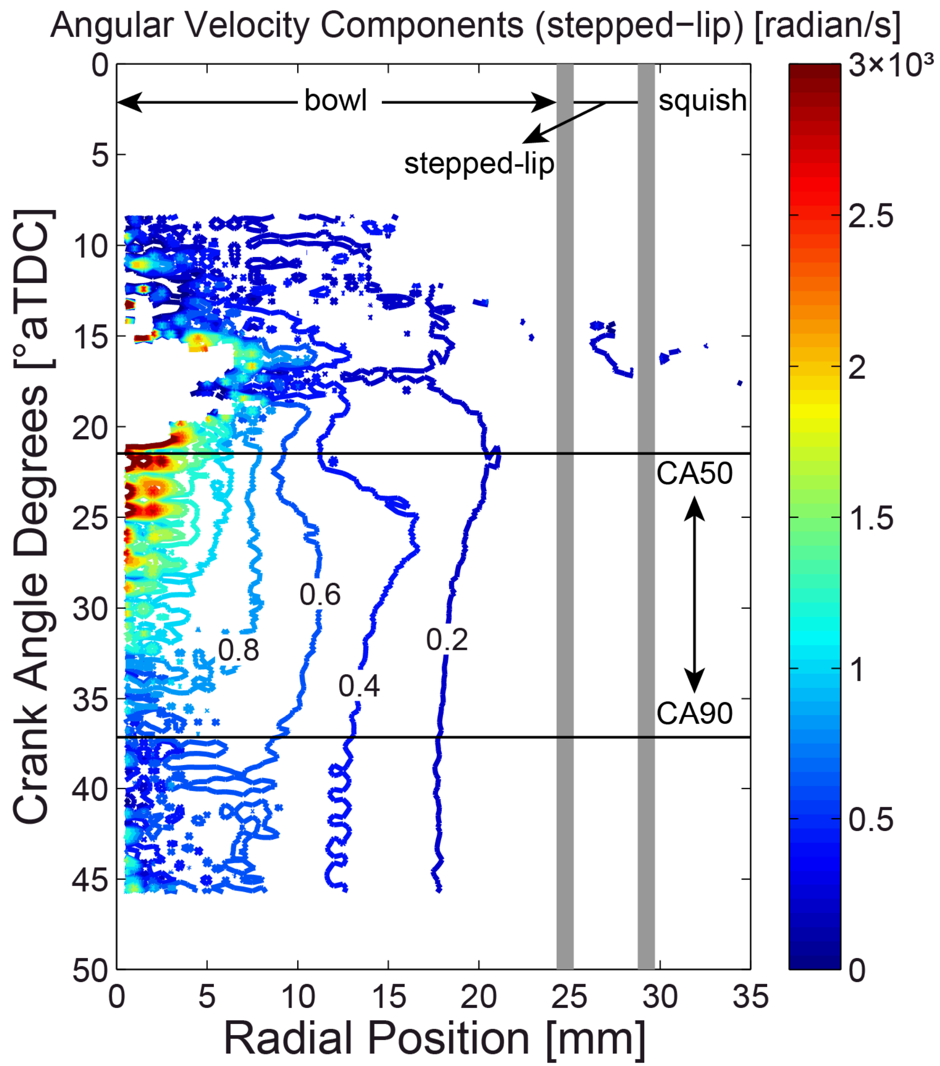
Late combustion duration seems to correlate with the temporal interval in which angular velocity is amplified.





Amplified swirling magnitudes do not seem to be the reason for fast late-cycle combustion.





Summary

- Under medium load (9 bar), conventional combustion regime, Although regardless of similar combustion phasing (CA10-CA50) is between two geometries, a different combustion-induced flow structure is observed with CIV.
- Soot clouds tend to penetrate radially into the squish region for re-entrant bowl (CA10-CA50) which may be responsible for its higher angular velocity increase during late-stage combustion.
- Late combustion duration seems to correlate with the temporal interval in which angular velocity is amplified.
- Amplified swirling magnitudes do not seem to be the reason for fast late-cycle combustion.

Future work

- Process CIV results with different injection schedules (SSE_{pilot}=-17ºaTDC and 2ºaTDC).
- Quantify CIV-resolved RMS to estimate piston bowl geometry impacts on turbulent mixing.
- Compare flow measurement results with CFD results (Federico Perini, UW) to evaluate predictive simulation capabilities and provide guidance for future modeling efforts.

THANK YOU FOR YOUR ATTENTION !
QUESTIONS?