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Piston Geometry Effects on Fuel-Air Mixture Preparation in a Light-Duty Optical Diesel Engine

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Eric Kurtz (Ford)

Alok Warey, Dick Pe)

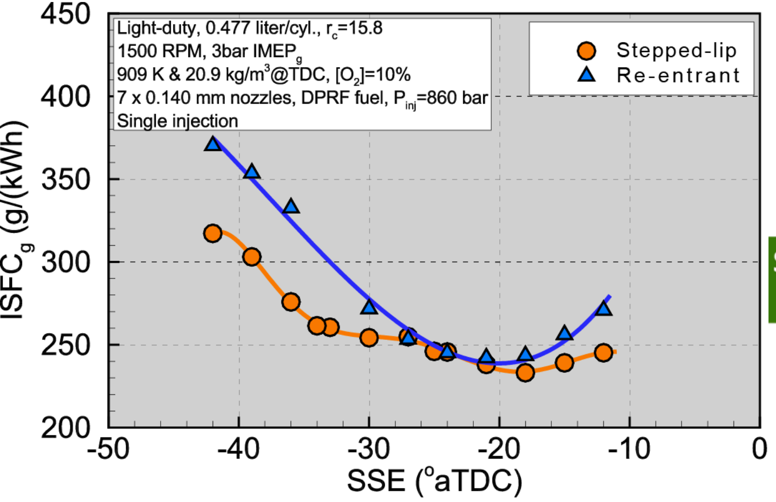
Abstract

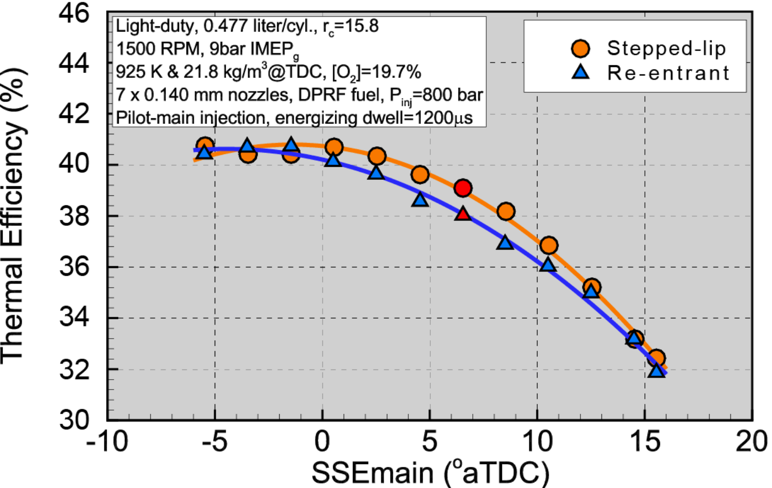
It is widely reported in the literature that for direct-injection Diesel engines, stepped-lip piston geometry exhibits fuel efficiency and emission advantages over re-entrant piston geometry at some injection timings. This observation is present both under low-load EGR-diluted Low-Temperature Combustion (LTC) and medium-load conventional diesel combustion regimes. However, this geometry-induced mechanisms f[illegible] increased heat release rates and higher combustion and/or thermal efficiency is not fully understood. In or[illegible] understand the mechanism, experimental investigation of piston geometry effects on fuel-air mixture pre[illegible]eeded. This work utilizes a fuel tracer laser-induced fluorescence (LIF) technique to conduct [illegible]rusiv[illegible]nar measurements of in-cylinder fuel distribution under non-combusting conditions insi[illegible]cylinder sh[illegible] bore optical Diesel engine. In this study, two transparent piston bowls - adapti[illegible]l re-en[illegible]nt and stepped-lip geometry respectively - are compared. By taking area-ave[illegible]raction i[illegible]r-coordinate fashion, the temporal and spatial trends show that [illegible]ry tends to [illegible] injected fuel on the lip shoulder, which promotes better bo[illegible]lization and m[illegible] prevent unburnt fuel from penetrating into the squish region by[illegible]squish flow. Furth[illegible]ental [illegible]nd computational investigations such as high-speed ima[illegible]linder soot natur[illegible]d turbu[illegible] mixing, speed/load/spray targeting sensitivities an[illegible]eeded to study[illegible]ced bene[illegible] clean and efficient diesel combustion.

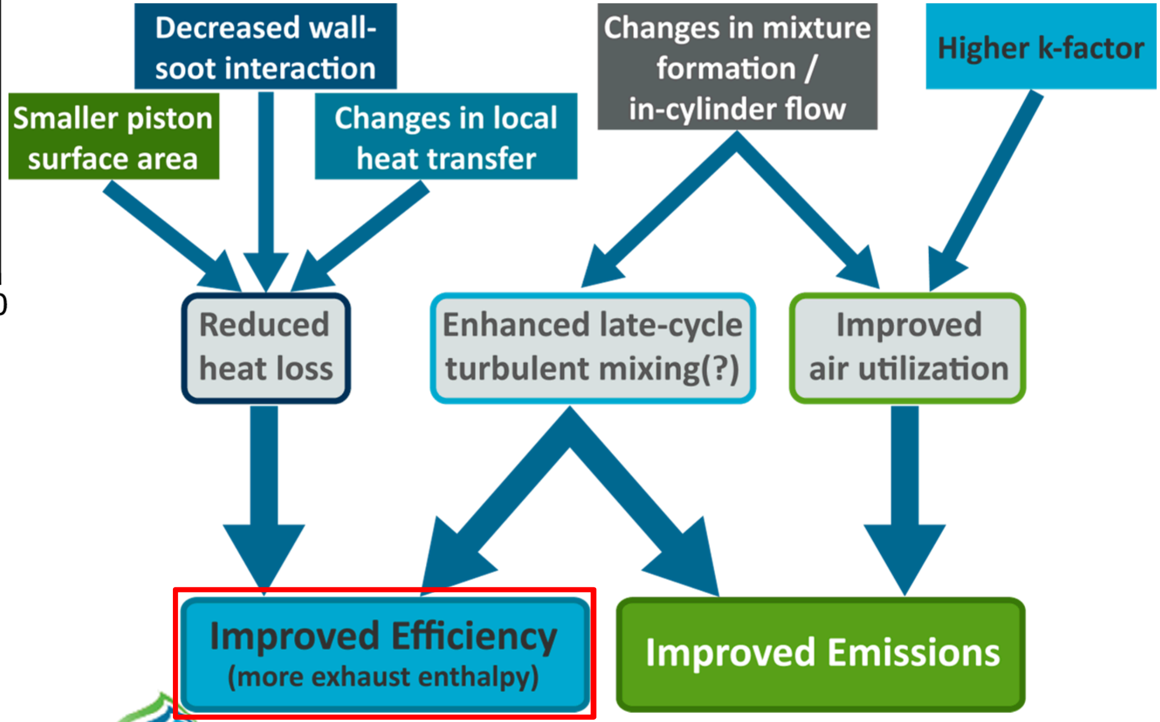
Outline

- Introduction and motivation
- PLIF experimental setup
  - SNL optical piston bowl geometries
- PLIF: data collection and processing
  - Uncertainties of PLIF measurements
- Area-averaged fuel mole fraction analysis
  - Single-injection, EGR-diluted LTC regime
  - Double-injection, conventional diesel co
- Conclusion

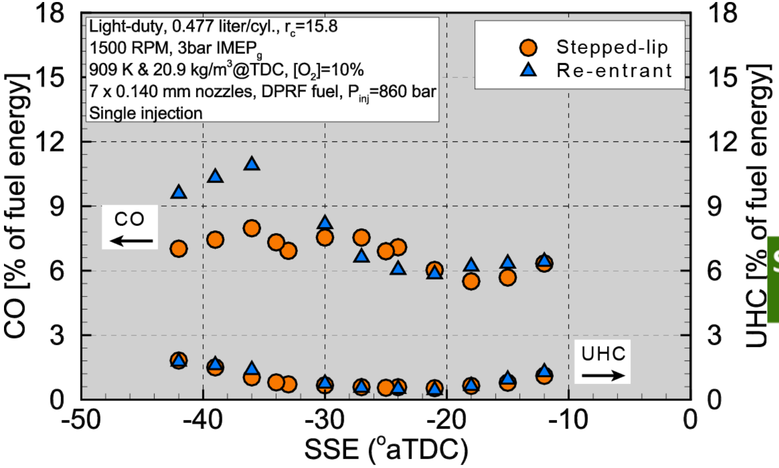
What makes the stepped-lip bowl more efficient than the conventional bowl?

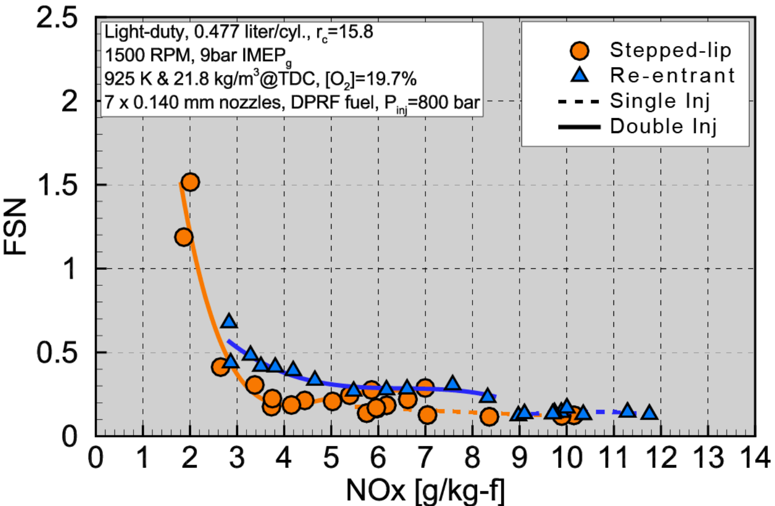


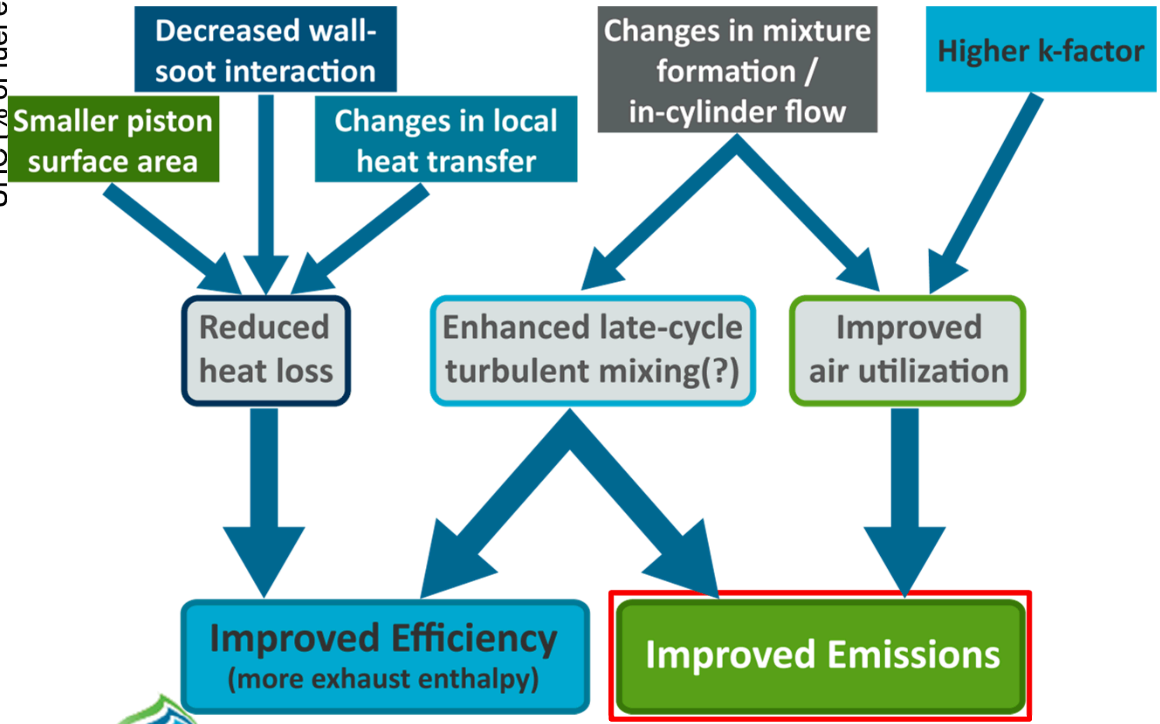




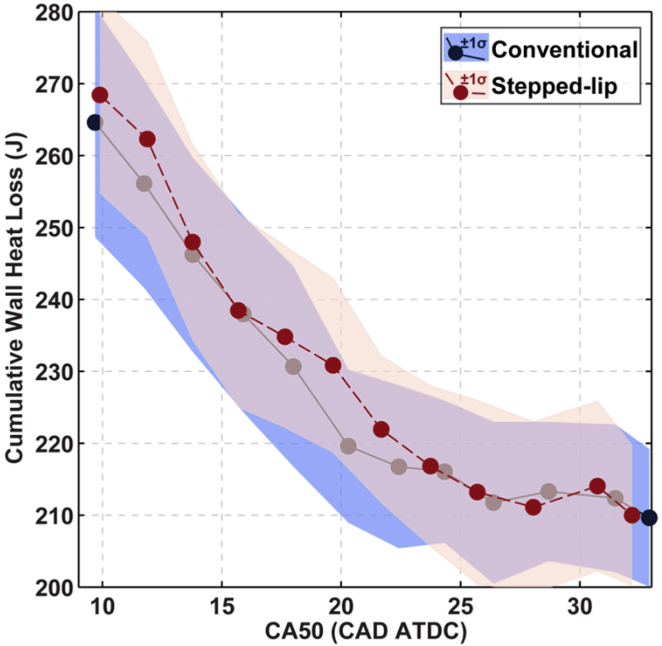
What makes the stepped-lip bowl more efficient than the conventional bowl?

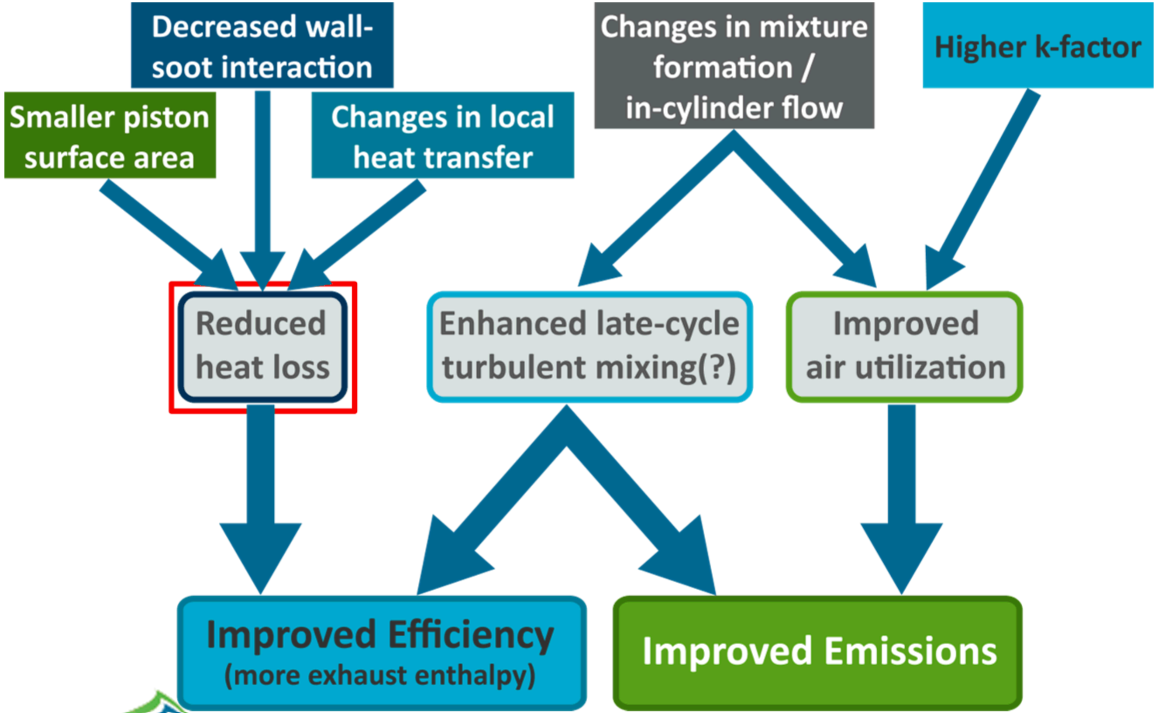




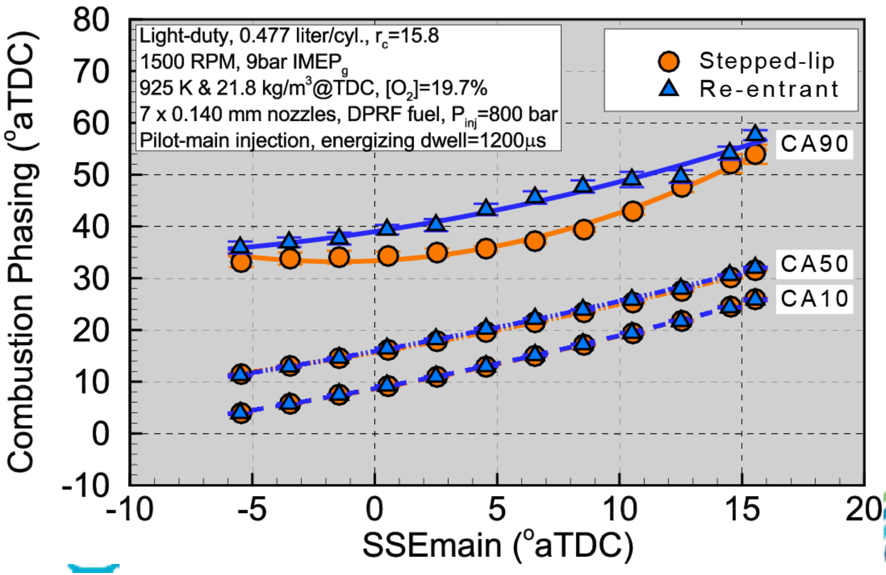


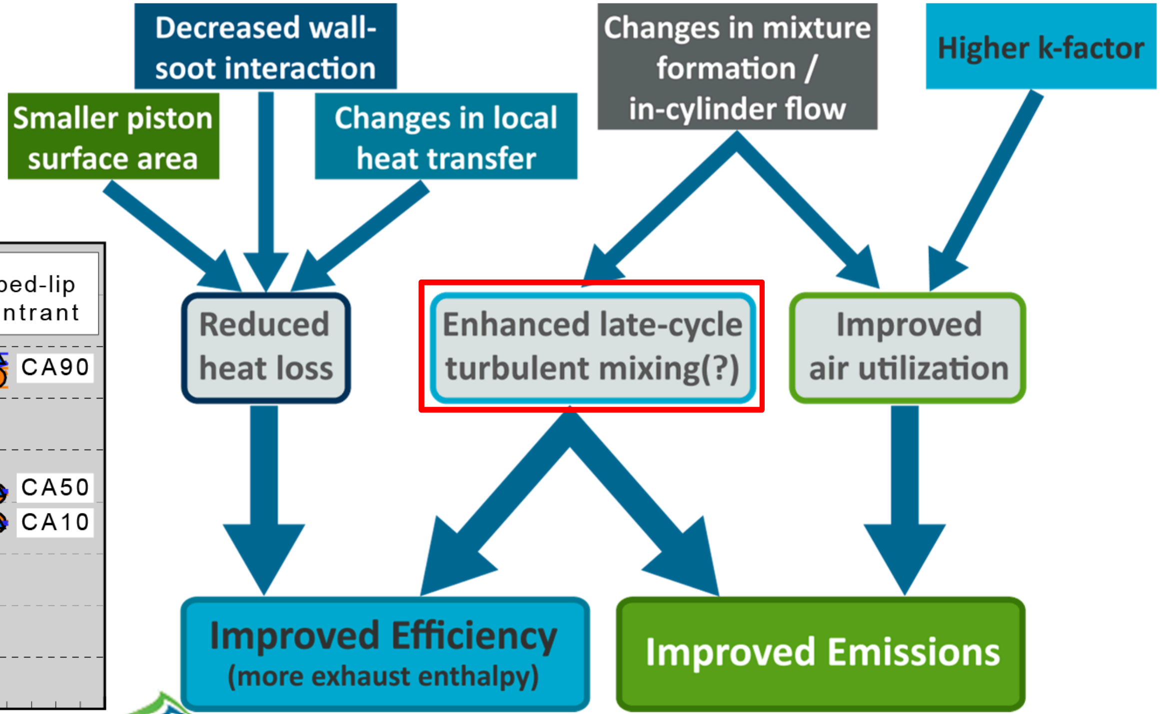
“Cycle-resolved analyses do not suggest lower wall heat loss with the stepped-lip piston bowl geometry.”





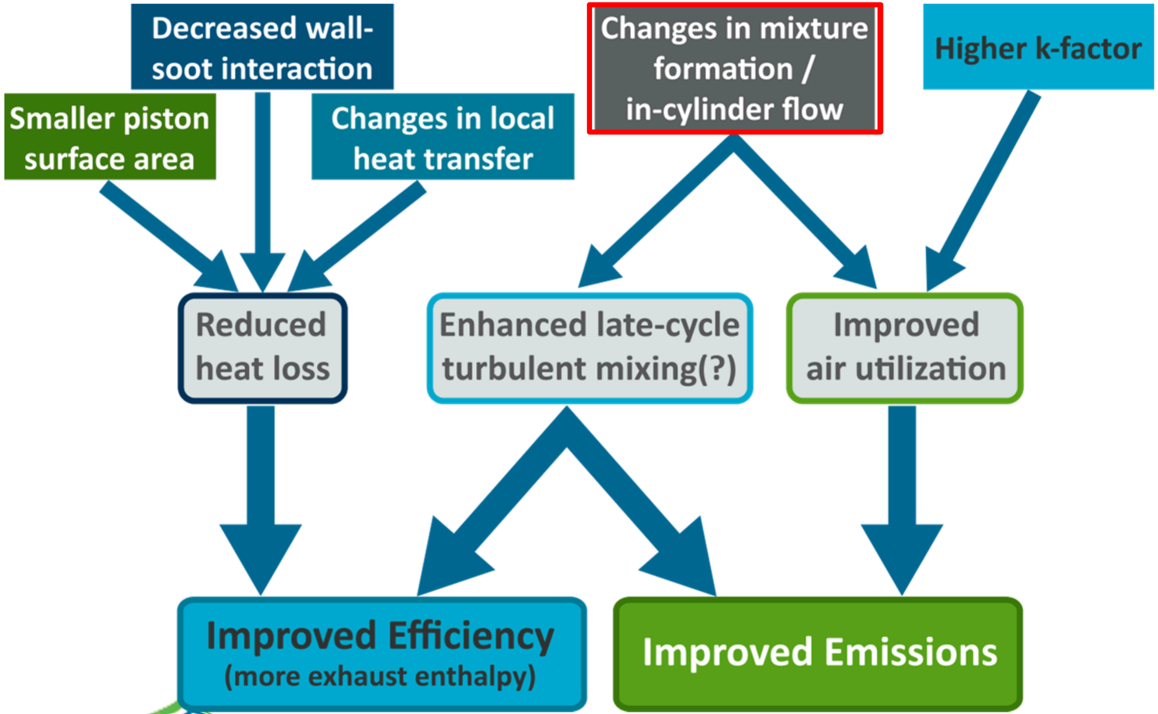
"Fuel conversion efficiency improvements with the stepped-lip piston are most closely related to enhanced late-cycle heat release rates."





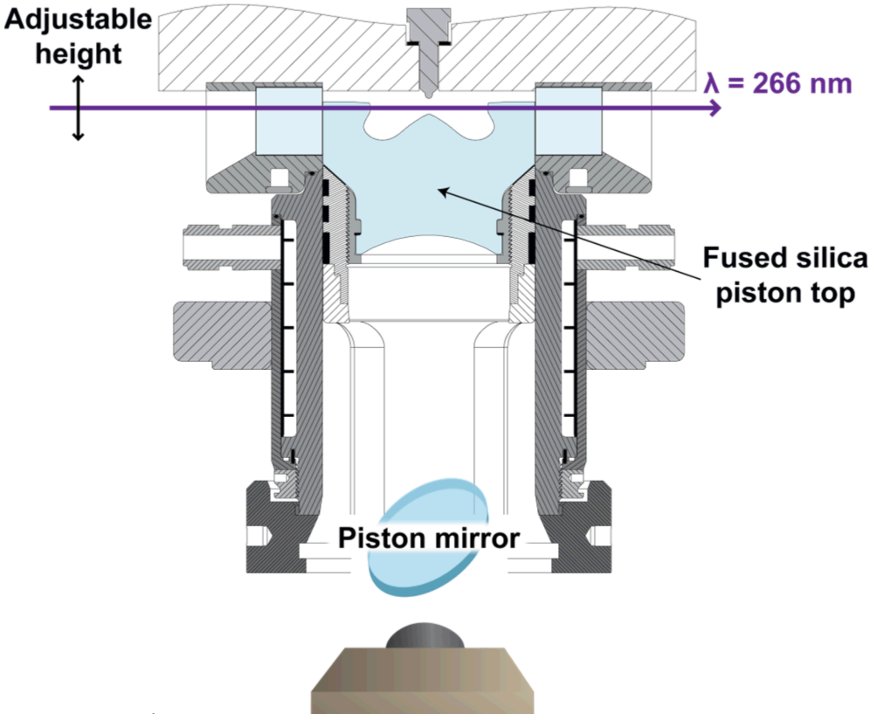
Does stepped-lip piston result in a mixture formation distribution more favorable for complete combustion and enhanced turbulent mixing?

- Does piston-induced changes in cold flow structure have big effects on mixture preparation?
- What is the role of squish flow?
- Spray-piston interaction?



PLIF Experiments in the SNL 0.48L light-duty single-cylinder optical engine

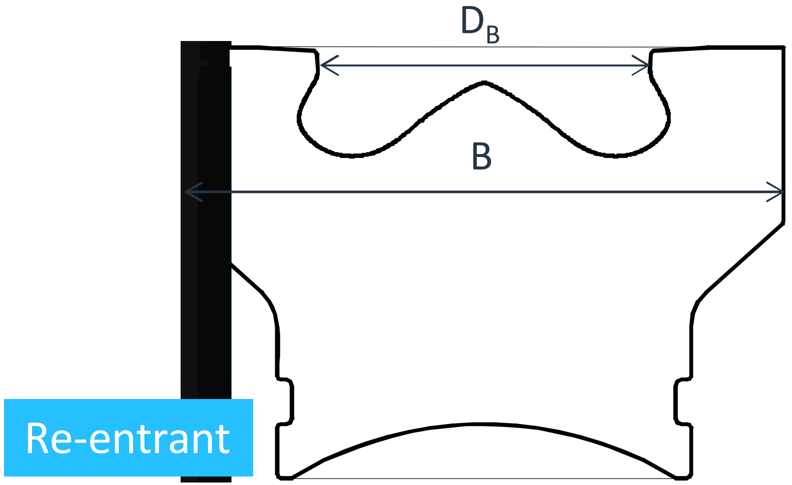
- Engine operation
  - 1500 rpm
  - Non-combusting, 0% O_2
  - Fuel: 42 vol% n-hexade... + 58 vol% heptamethylnonane
  - Tracer: 0.5 weight% ...hylna...alene
  - Swirl ratio: 2...
- Illuminati...
  - ...rmonic (266...
  - ...mJ/pulse (relativ... ...y measure... each shot)
  - Laser s... ...1 mm
- Ima...
  - ...X4 ICCD camer...
  - Nikon UV-10...
  - WG... ...

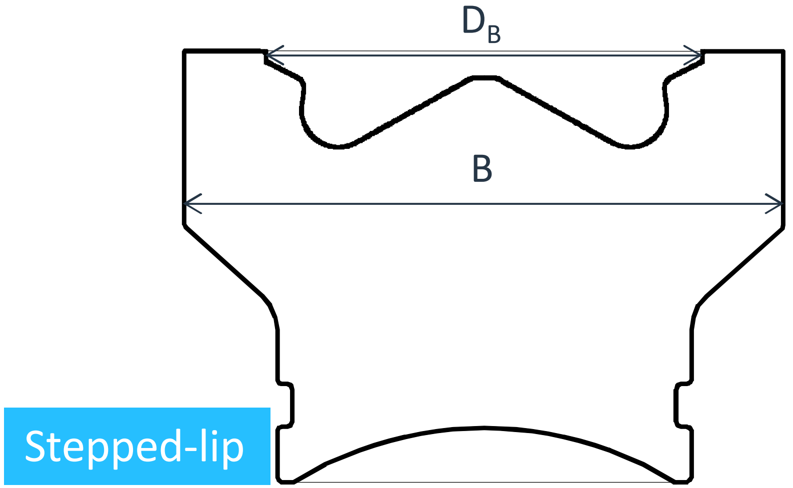


Bore x stroke	82 mm x 90.4 mm
Compression ratio	15.8:1
Valves	4
Injector type	Solenoid
Holes	7 x 139 µm
ks	1.5/86
Included Angle	149°

SNL optical piston bowl geometries

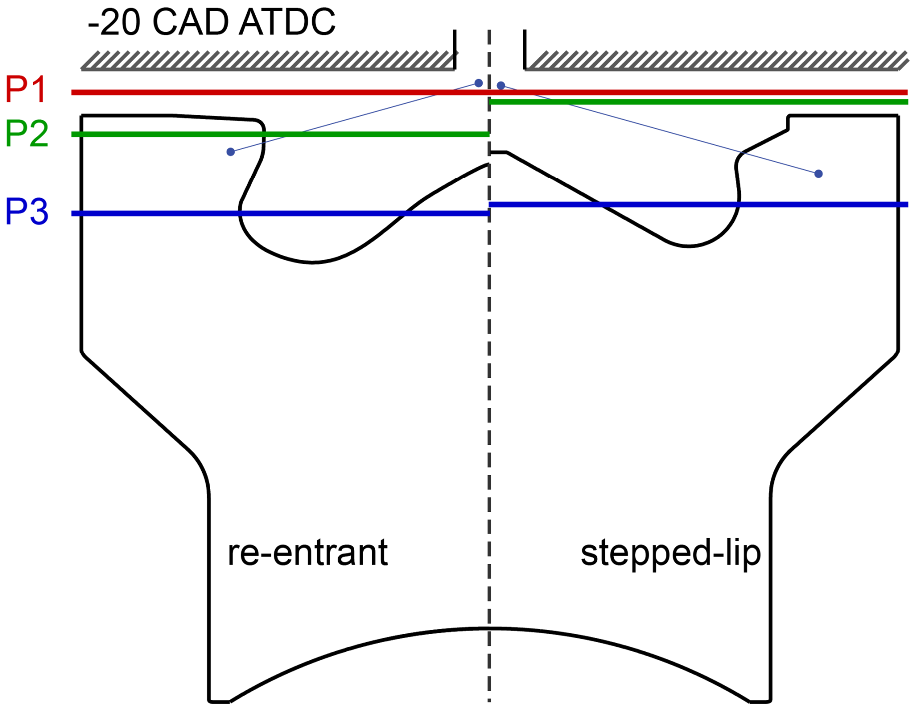
- Two quartz pistons have identical:
  - Bowl volume = 0.028 L
  - Squish height = 1.35 mm
  - Compression ratio = 15
  - No valve cut-outs
- Different bowl ge… …esult in …ferent bowl-to-bore …
  - R… ….55
  - …p: D_B/B=0.73
- …ace area of ste… …owl is …0% less than fo… …onal bo…
- Ini… …ration is s… …on …endations fr… …ners





PLIF setup: laser plane locations

- Plane 1 (P1) is set half of squish height
- Plane 2 (P2) is empirically determined
  - Re-entrant: at rim of b… ere laser sheet passes through with … ction
  - Stepped-lip: 1.37 … ve the p… top
- Plan… deep with…
  - …rant: 9.88 mm b… piston to…
  - Stepped-lip: 8.9… the pis… top
- P2 … with the pi… rank …nges.



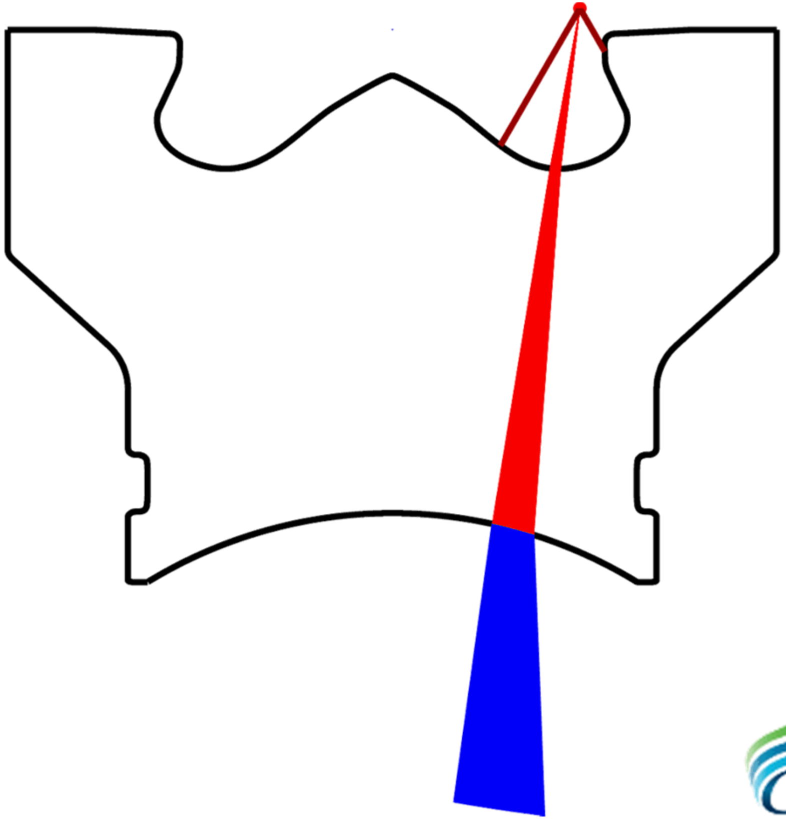
PLIF: data collection and processing

- Three sets of images for a given crank angle, plane, and operating point (51 images per set)
  - Background (no fuel injection)
  - Flat-field (6/8 injections in intake stroke)
  - Fuel injection image (desired operating point)
  - Fuel injection Image sets taken over range starting from injection ending prior to SOC.
- 9:15min's measurement schedule to maintain temperatures and pressures
- Distortion correction according to established ray-tracing routine

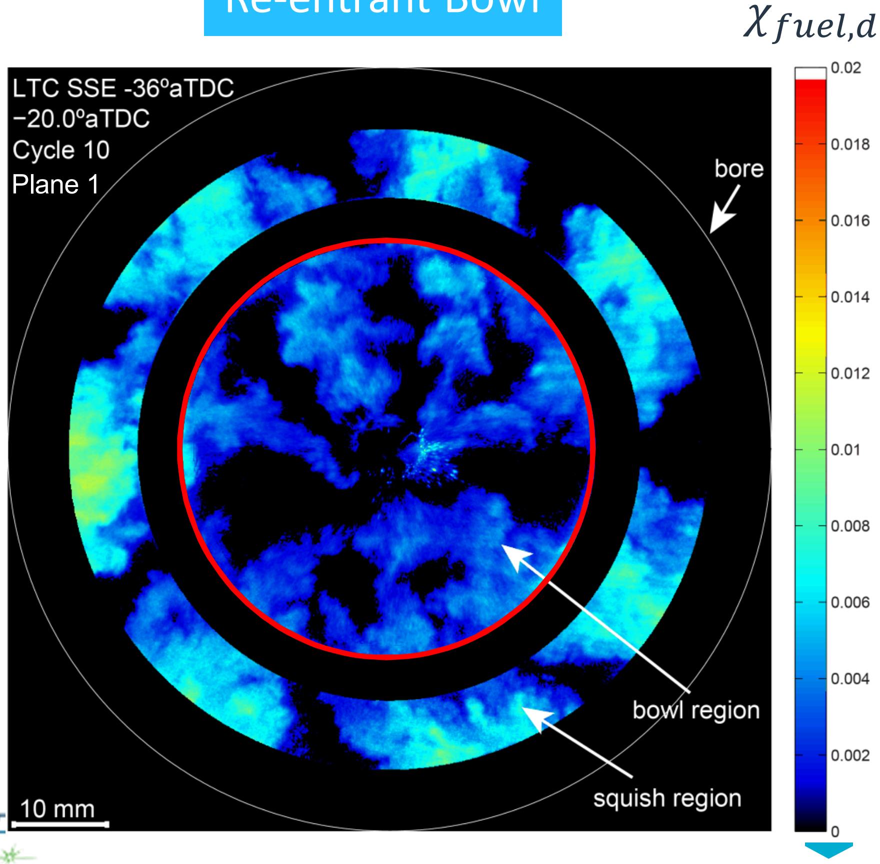
$$\chi_{fuel,d} = \chi_{fuel,cal} \frac{S_d}{S_{cal}} \frac{E_{cal}}{E_d} \frac{T_d}{T_{cal}} \frac{P_{cal}}{P_d} \frac{\sigma\eta(T_{cal})}{\sigma\eta(T_d)}$$

- $\chi_{fuel,d}$ = (moles nC16H34 + moles iC16H34 + moles 1MN) / (total moles of CO2, N2, nC16H34, iC16H34, and 1MN).

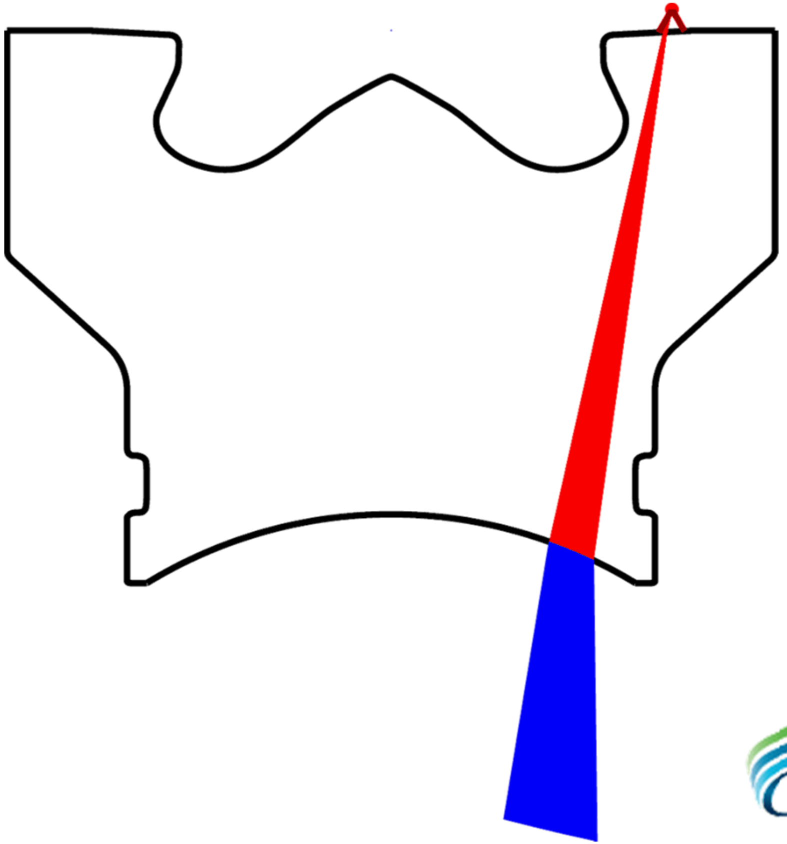
A sample of dewarped PLIF images with re-entrant geometry



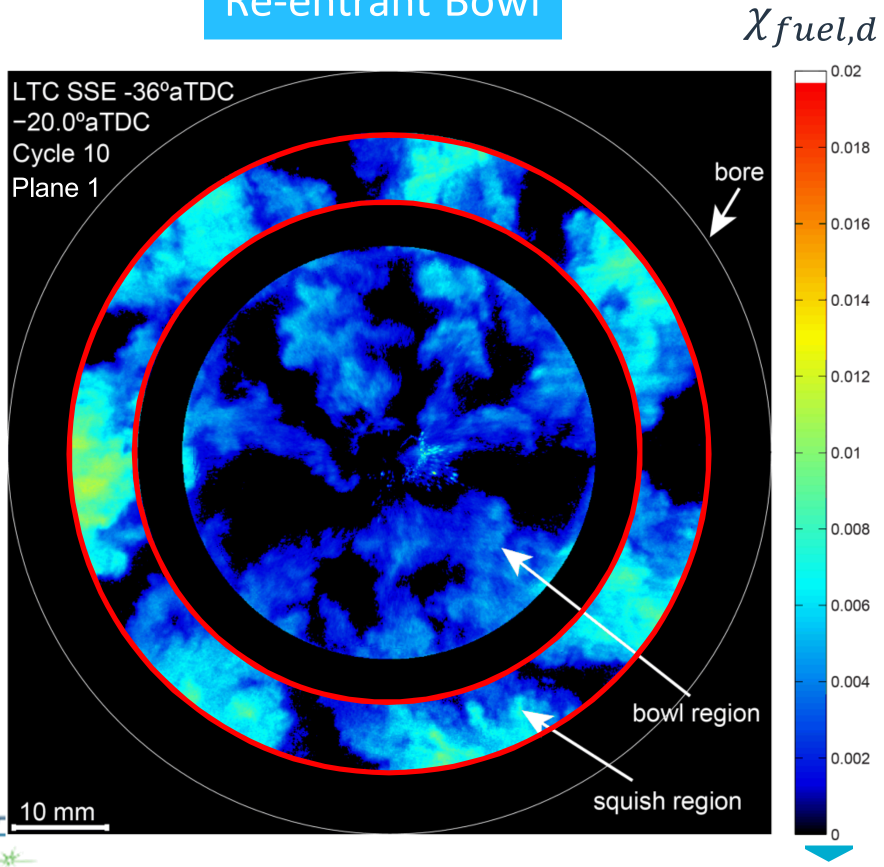
Re-entrant Bowl



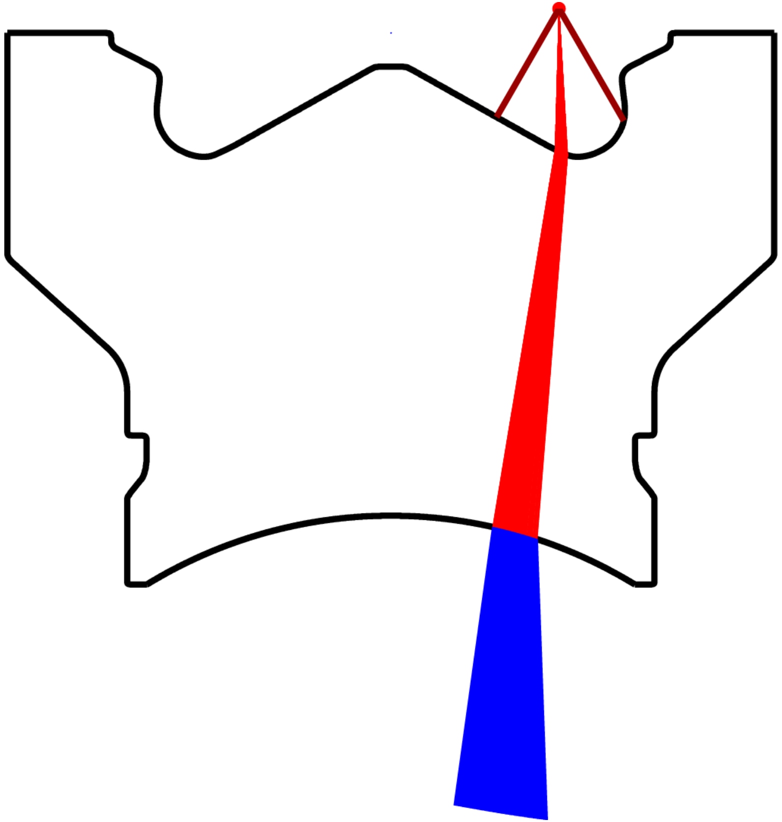
A sample of dewarped PLIF images with re-entrant geometry



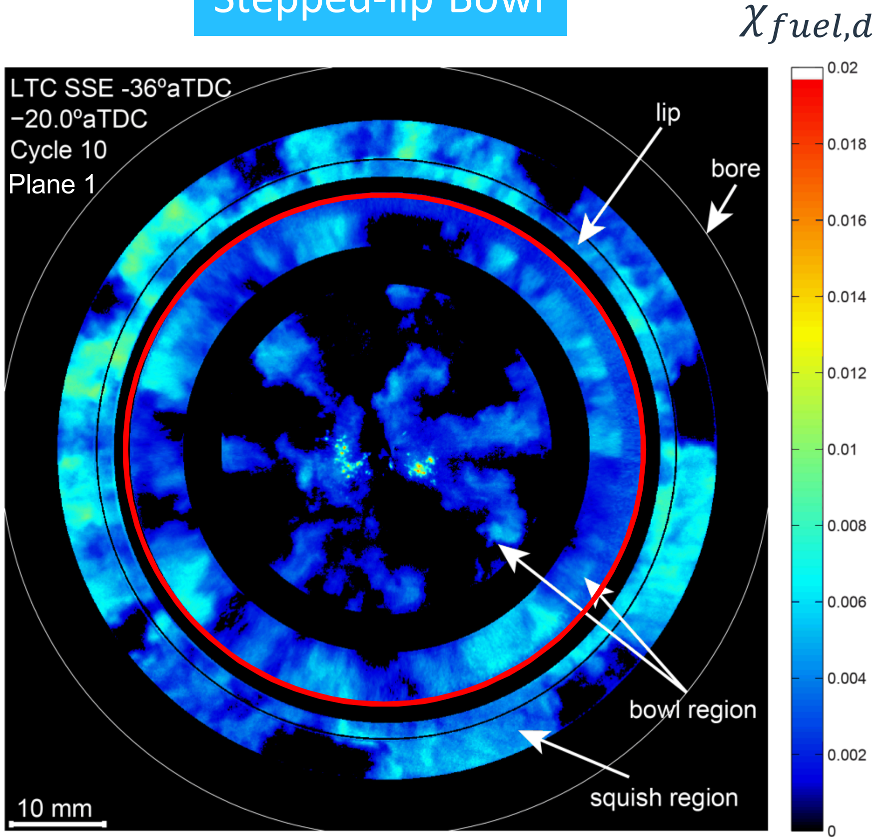
Re-entrant Bowl



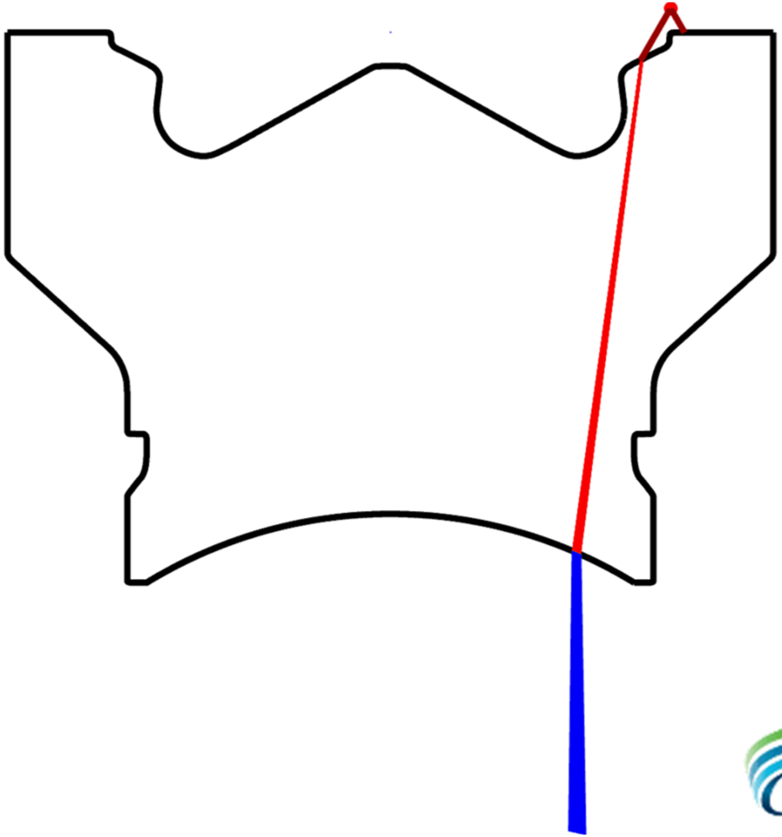
A sample of dewarped PLIF images with stepped-lip geometry



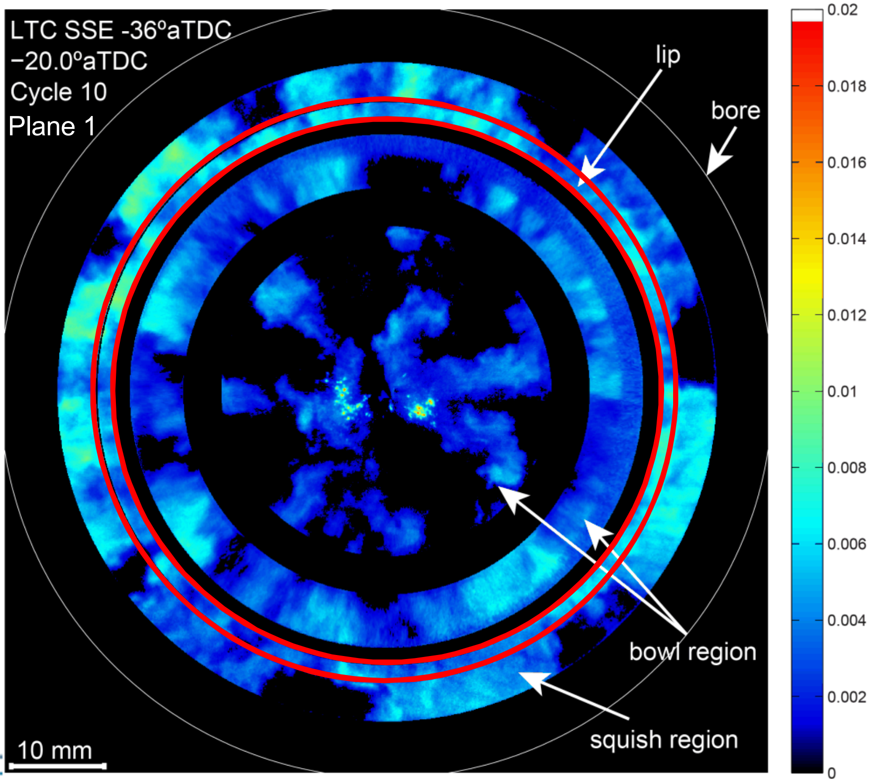
Stepped-lip Bowl



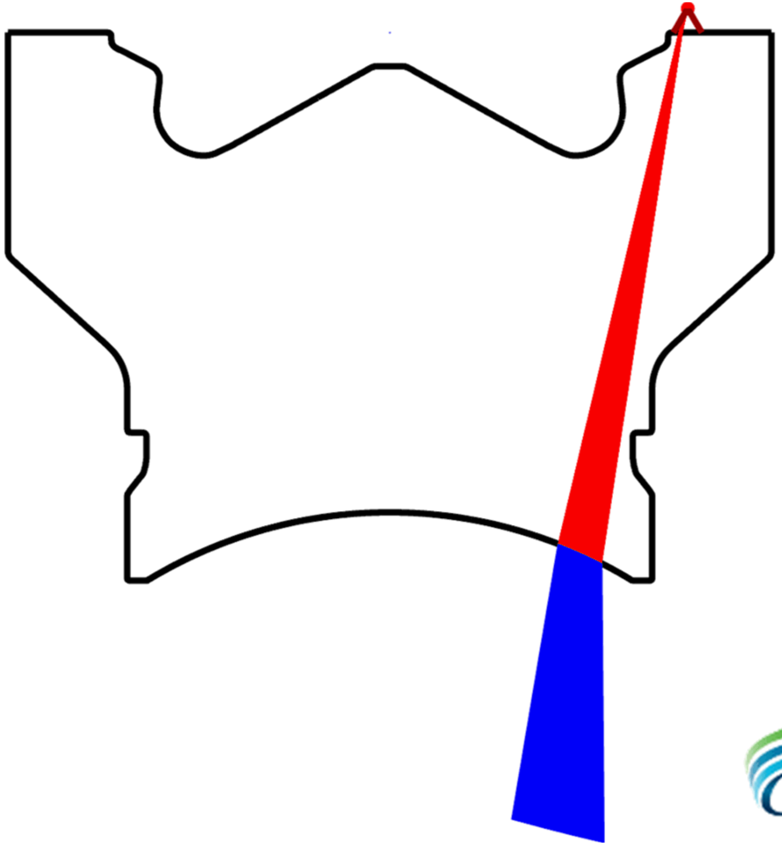
A sample of dewarped PLIF images with stepped-lip geometry

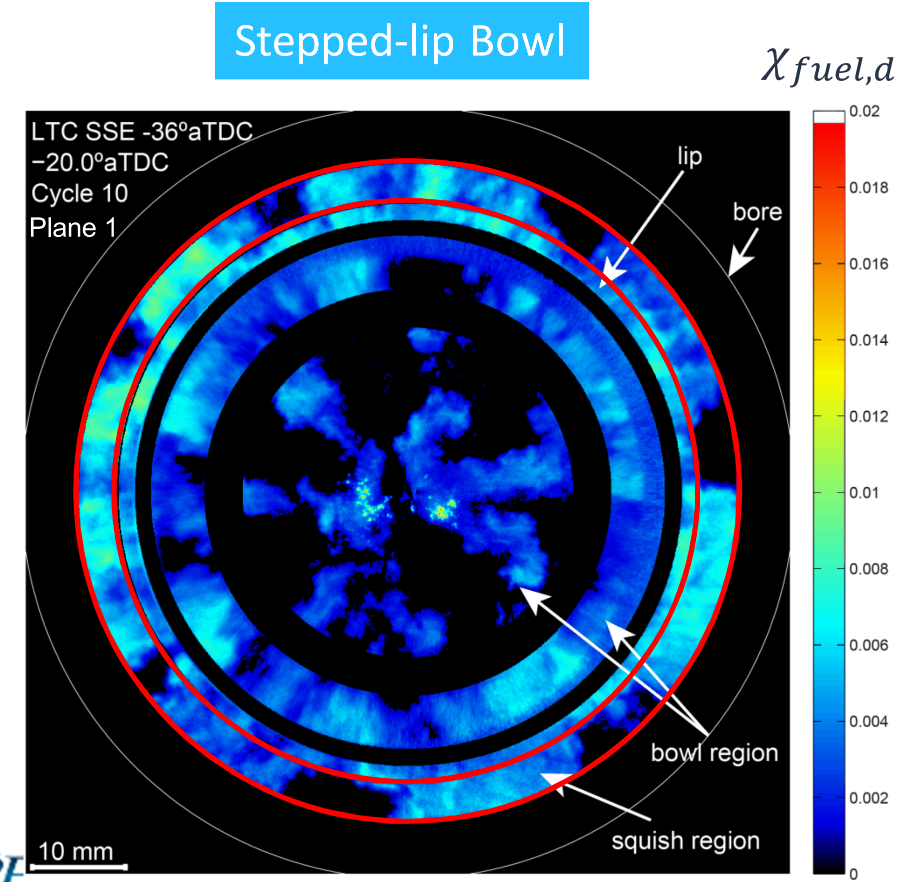


Stepped-lip Bowl



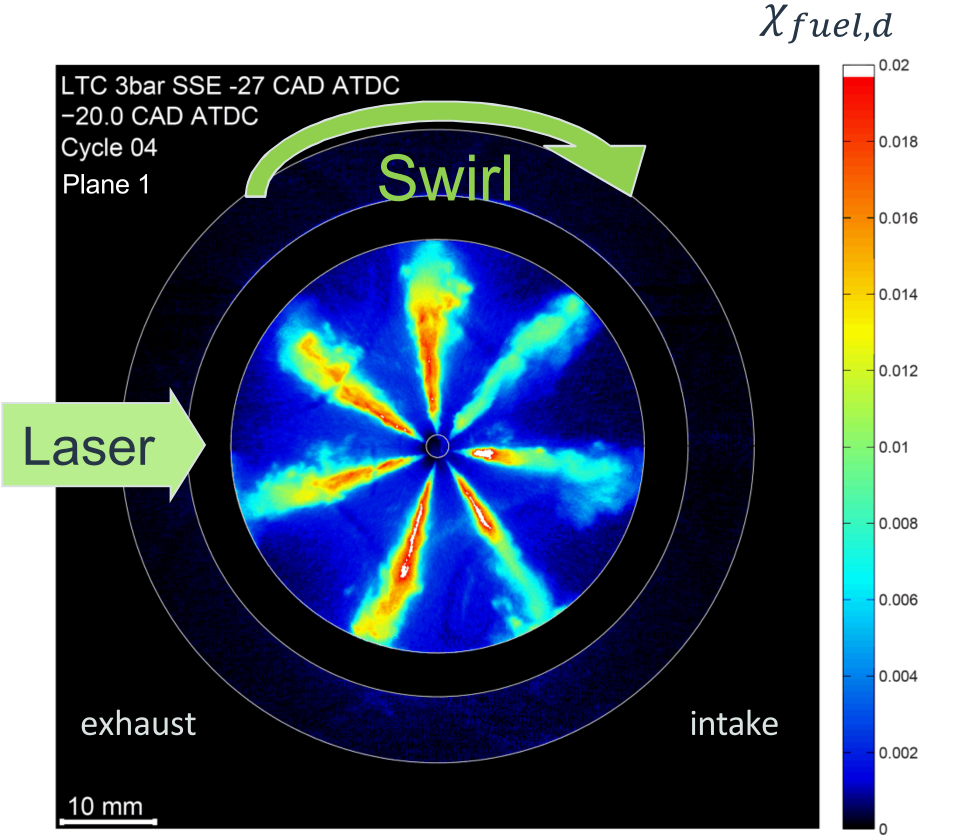
A sample of dewarped PLIF images with stepped-lip geometry





Uncertainties of PLIF measurements

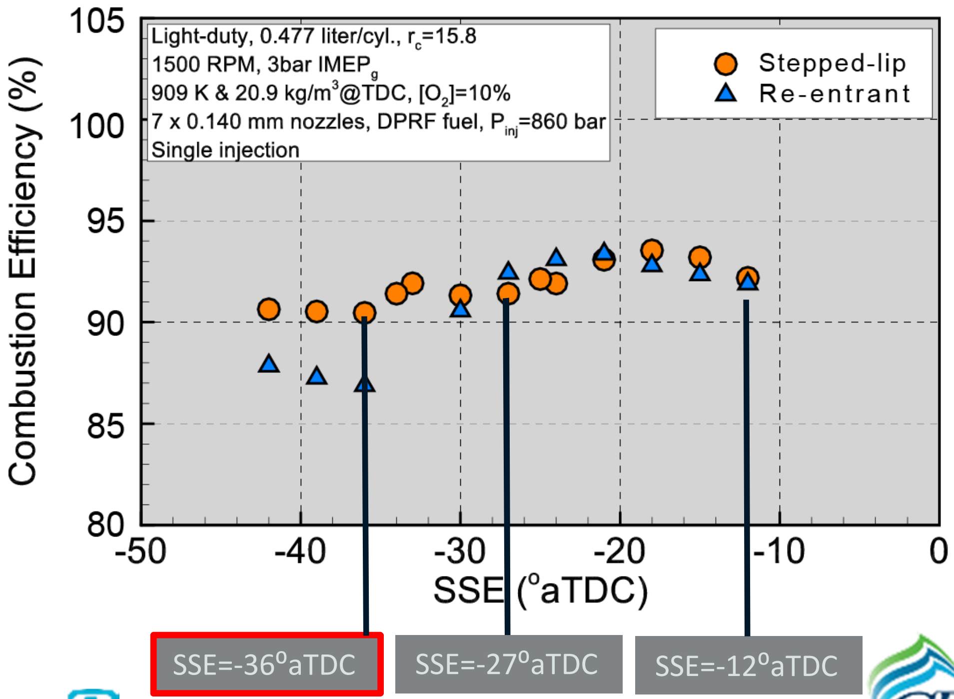
- Dewarping-induced error in radial locations: measurements near chamber center (R<~7mm) is not reliable.
- Camera nonlinearity at high intensities.
- Beam steering effects st... o show up in squish region when pi... in ±15 CAD around TDC.
- Plumes facin... g lase... rodu... more ... urements
  - ...dow caused by ... er inte... e.
  - ...t-of-plane fluores... from liquid brought by las... d backg... reflecti...
  - ... uorescence fr... light ... n chamber surf...



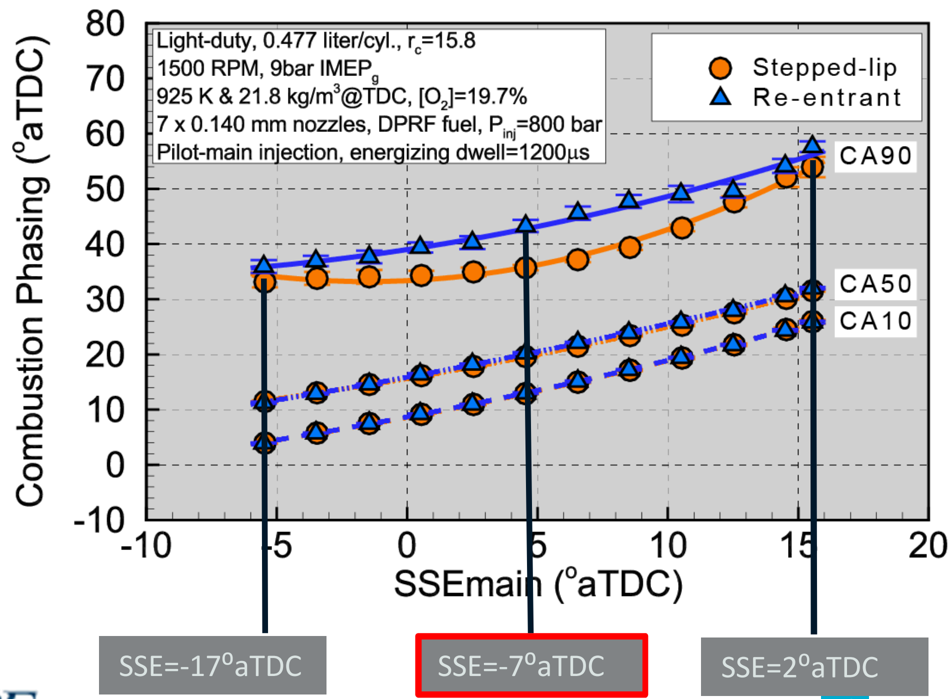
	CAD ATDC																						
	-26	-25	-24	-23	-22	-21	-20	-19	-18	-17	-16	-15	-14	-13	-12	-11	-10	-9	-8	-7	-6	-5	...	27
Images																								
Injection		SOI						EOI																
Combustion																					SOC			MBF90

Points of interest for optical investigation

Single-injection, EGR-diluted LTC regime

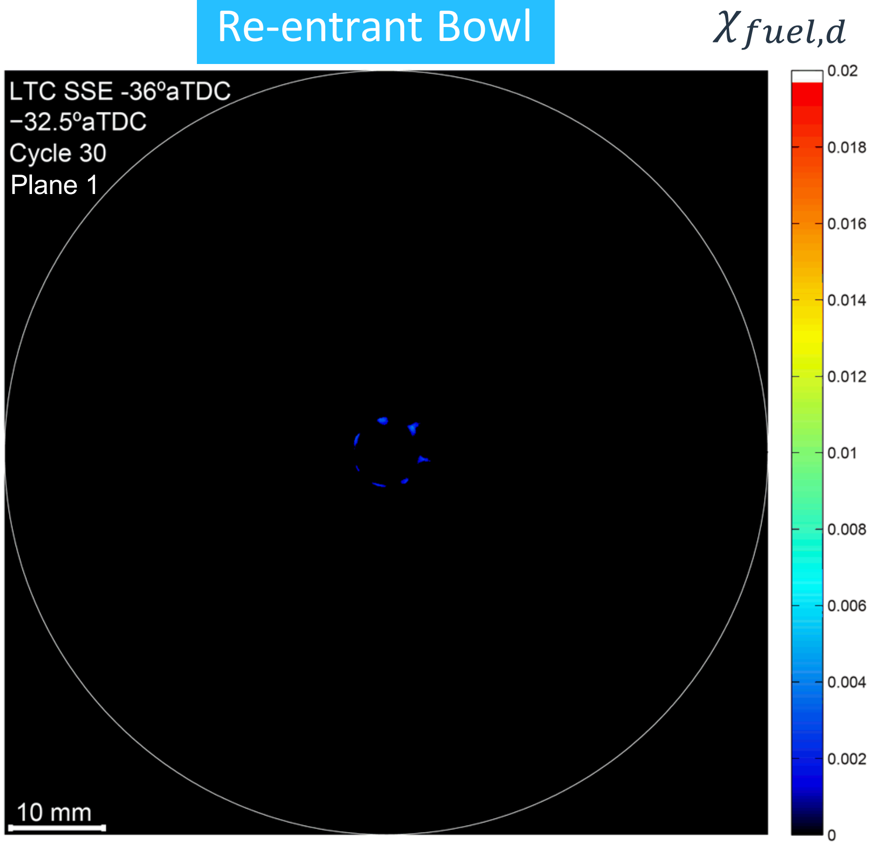


Double-injection, conventional combustion

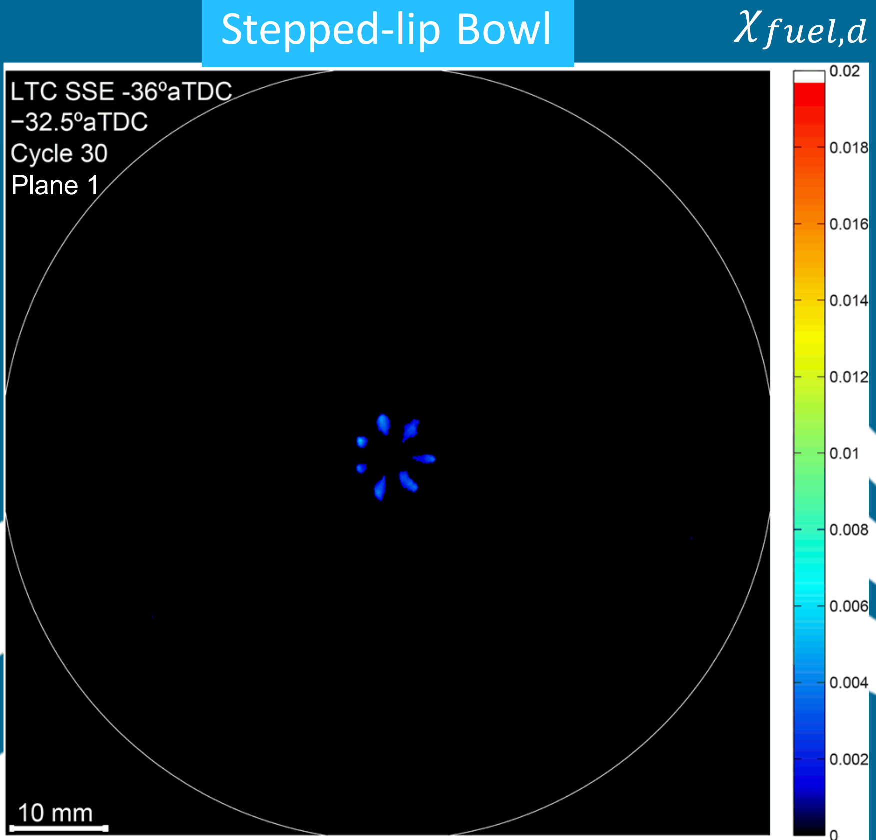


Is there a simple metric to quantify piston geometry impact on in-cylinder mixture preparation?

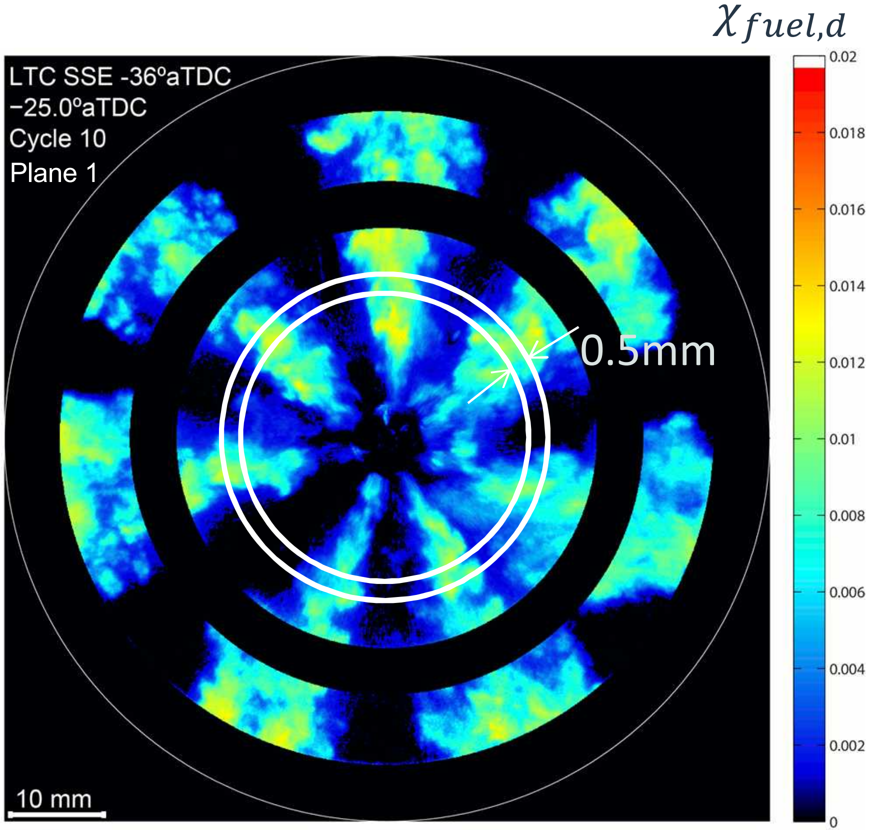
Re-entrant Bowl



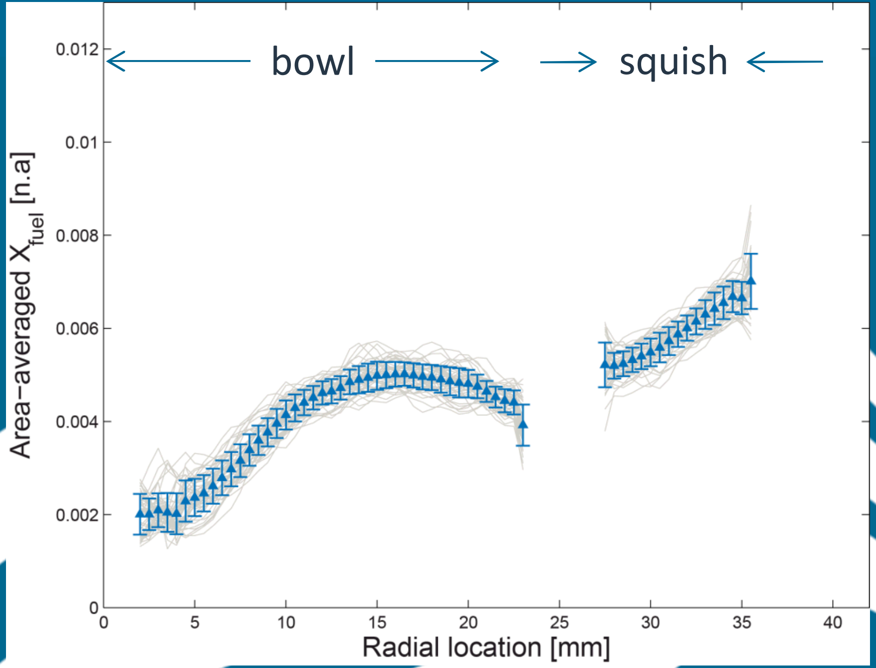
Stepped-lip Bowl



Area-averaged fuel mole fraction is calculated in polar coordinates to quantify spray-dominated mixture preparation pattern.



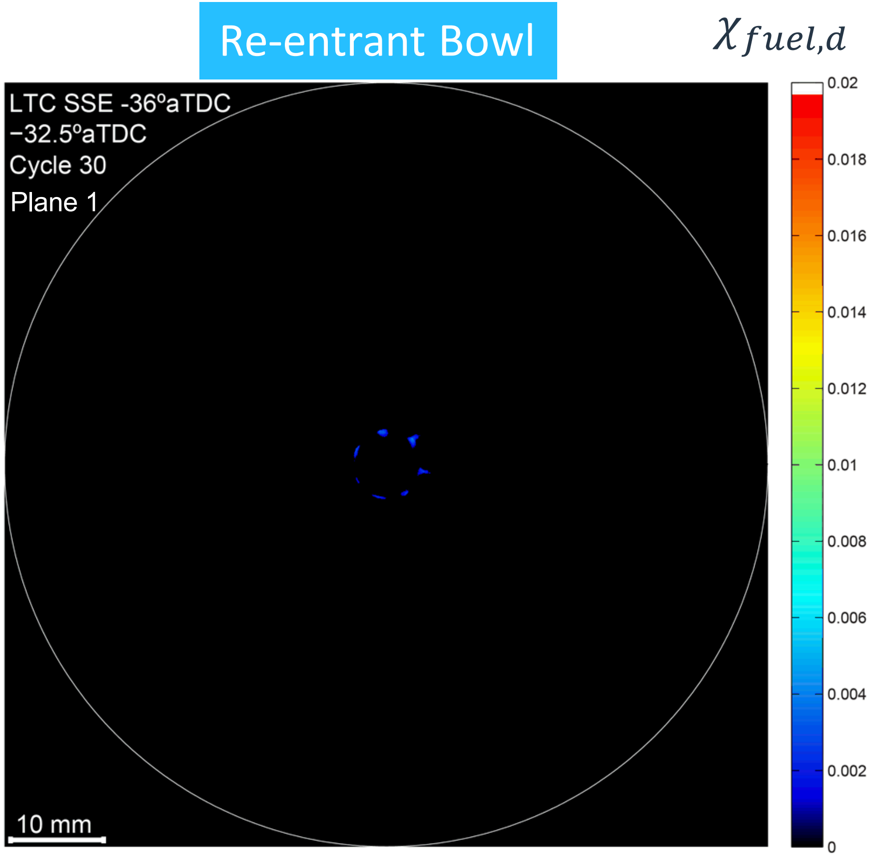
Area-averaged $\chi_{fuel,d}$



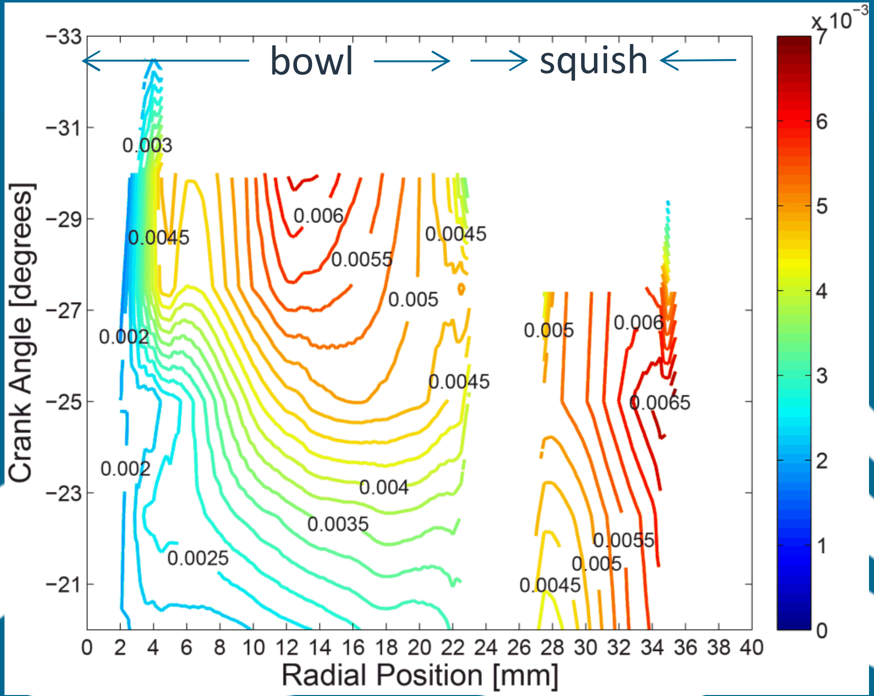
Error bar marks ±σ out of 50 realizations

Area-averaged fuel mole fraction with re-entrant bowl under LTC regime

Re-entrant Bowl



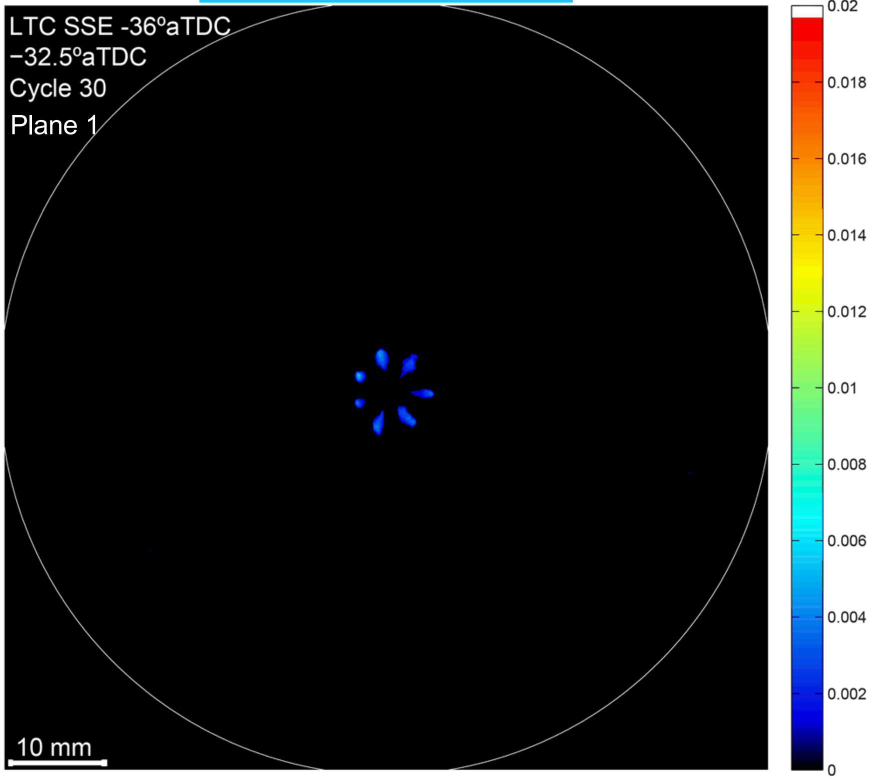
Area-averaged $\chi_{fuel,d}$



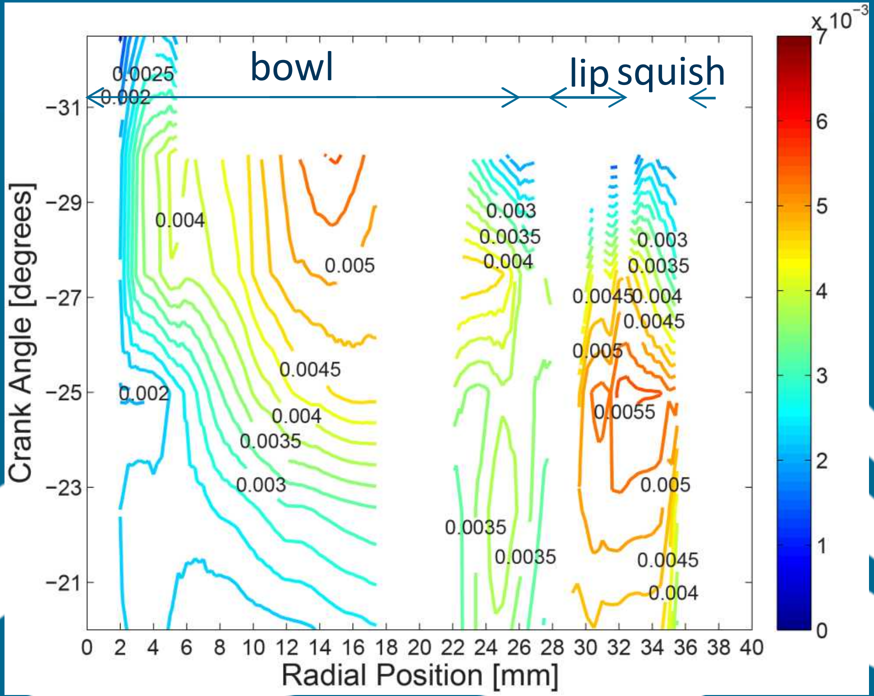
Area-averaged fuel mole fraction with stepped-lip bowl under LTC regime

Stepped-lip Bowl

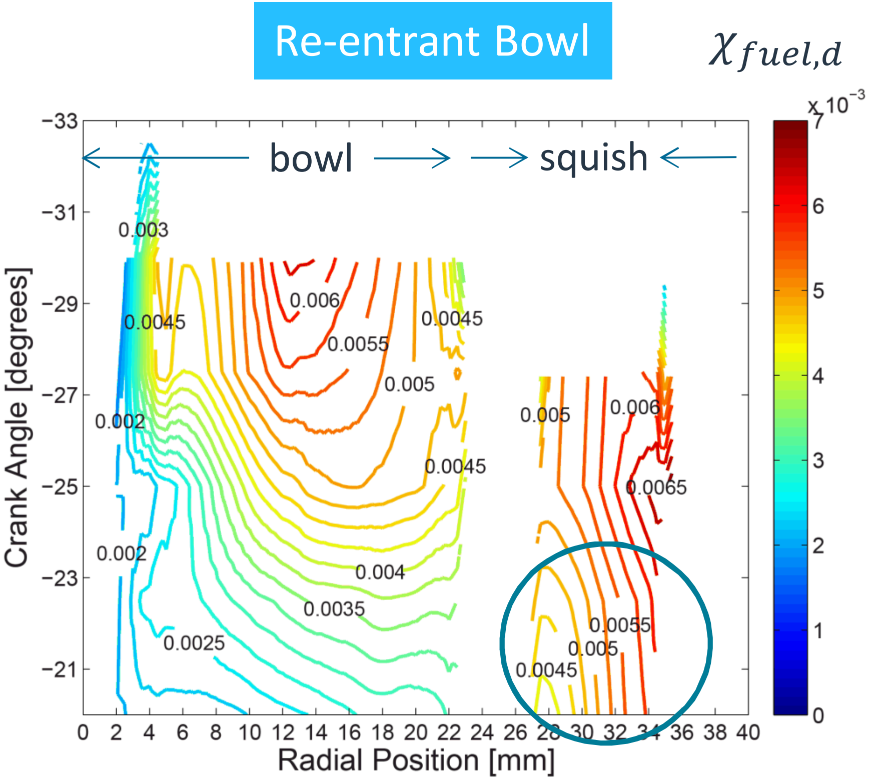
$\chi_{fuel,d}$

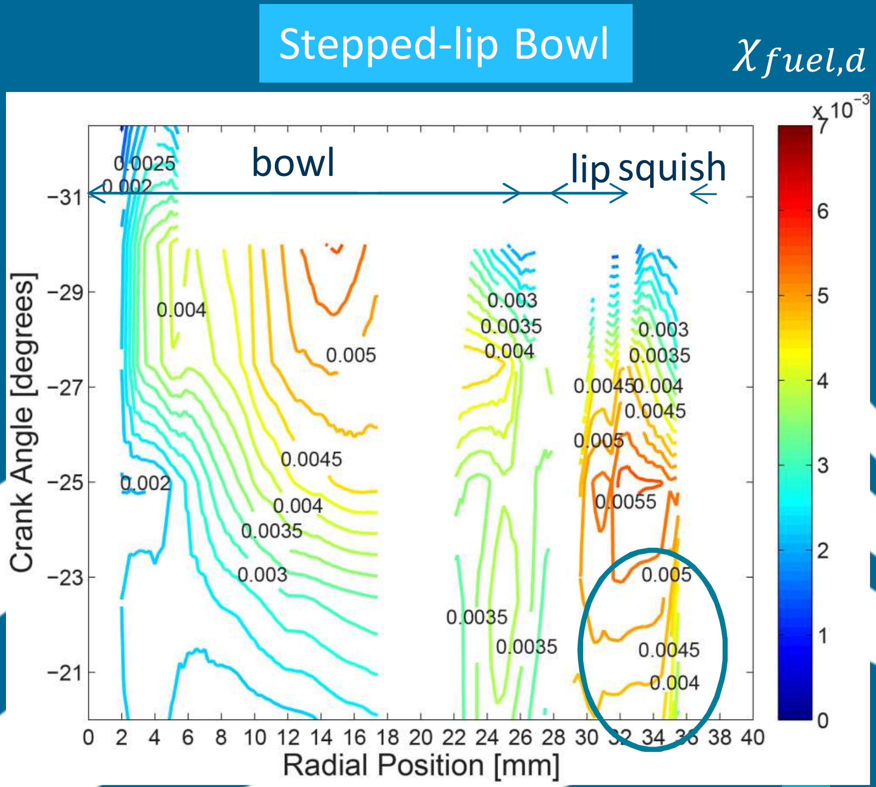


Area-averaged $\chi_{fuel,d}$



Stepped-lip piston exhibits leaner mixture formation in squish region under LTC regime.

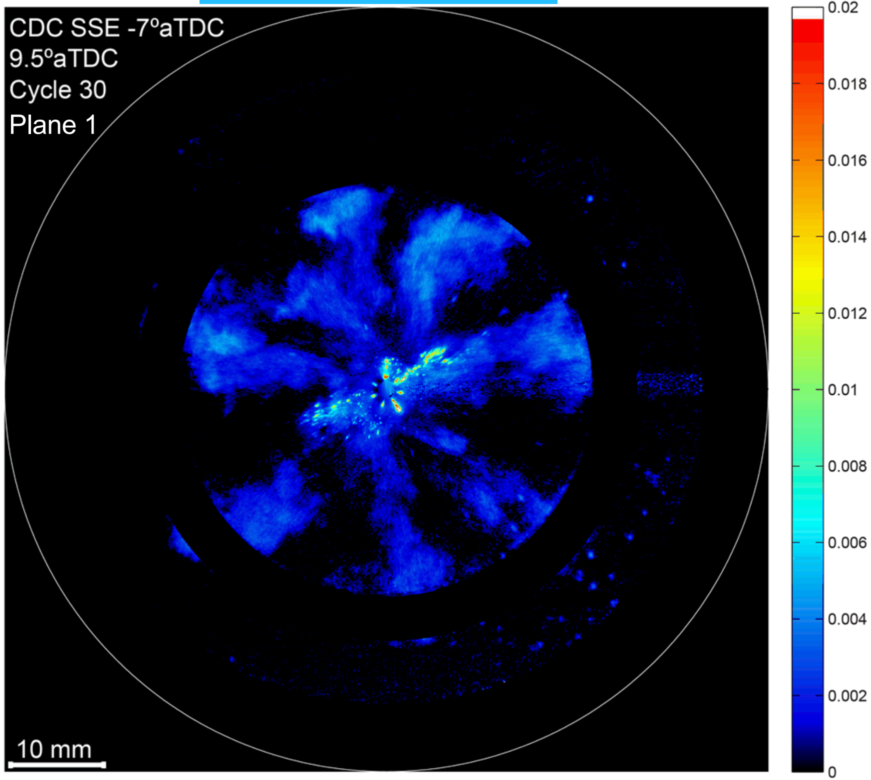




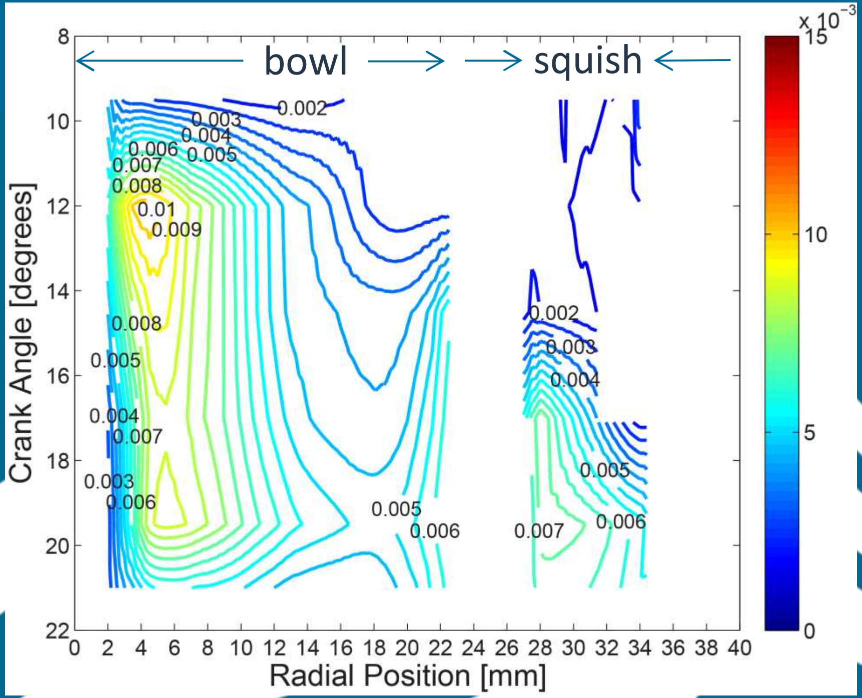
Area-averaged fuel mole fraction with re-entrant bowl under CDC regime

Re-entrant Bowl

$\chi_{fuel,d}$



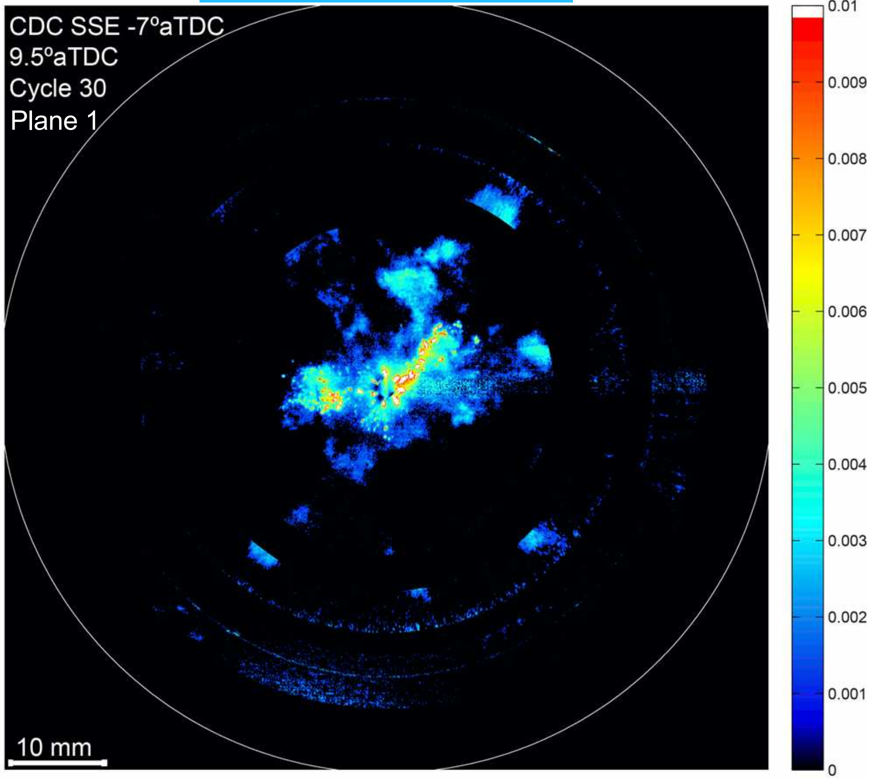
Area-averaged $\chi_{fuel,d}$



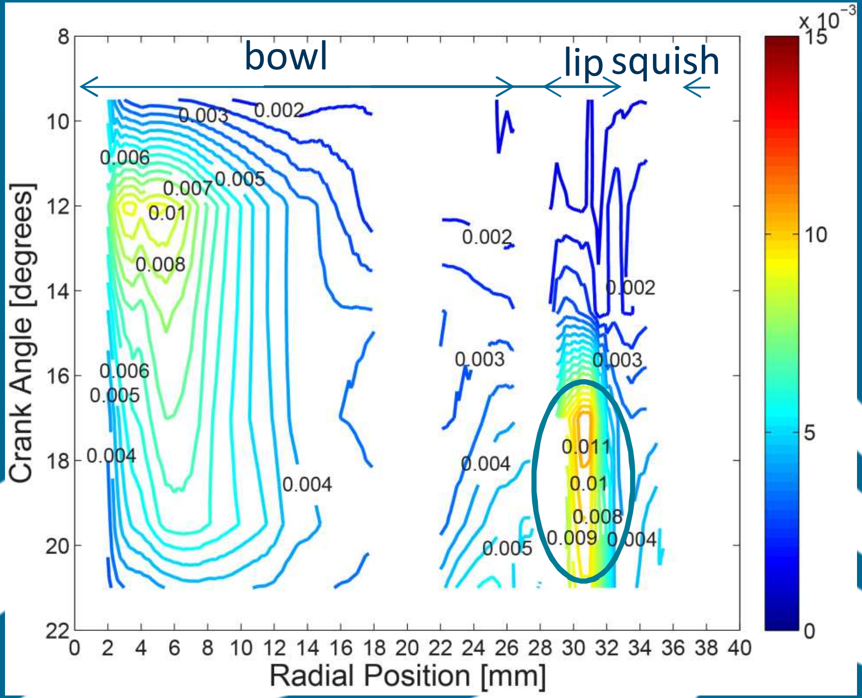
Area-averaged fuel mole fraction with stepped-lip bowl under CDC regime

Stepped-lip Bowl

$\chi_{fuel,d}$

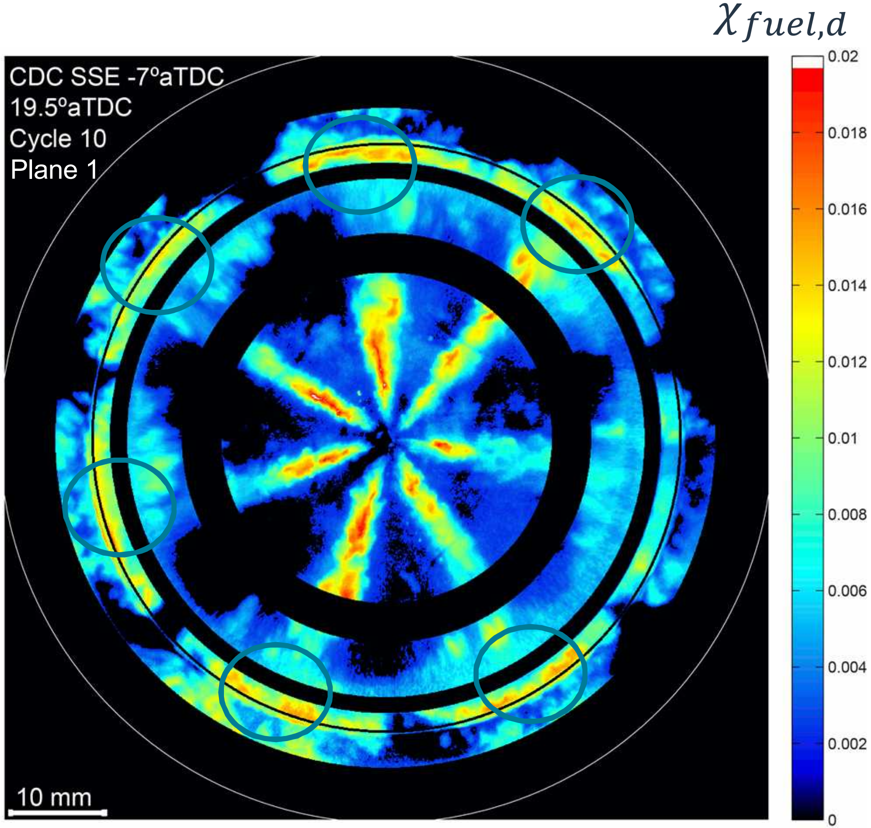


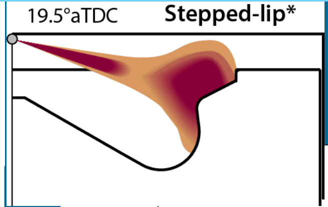
Area-averaged $\chi_{fuel,d}$



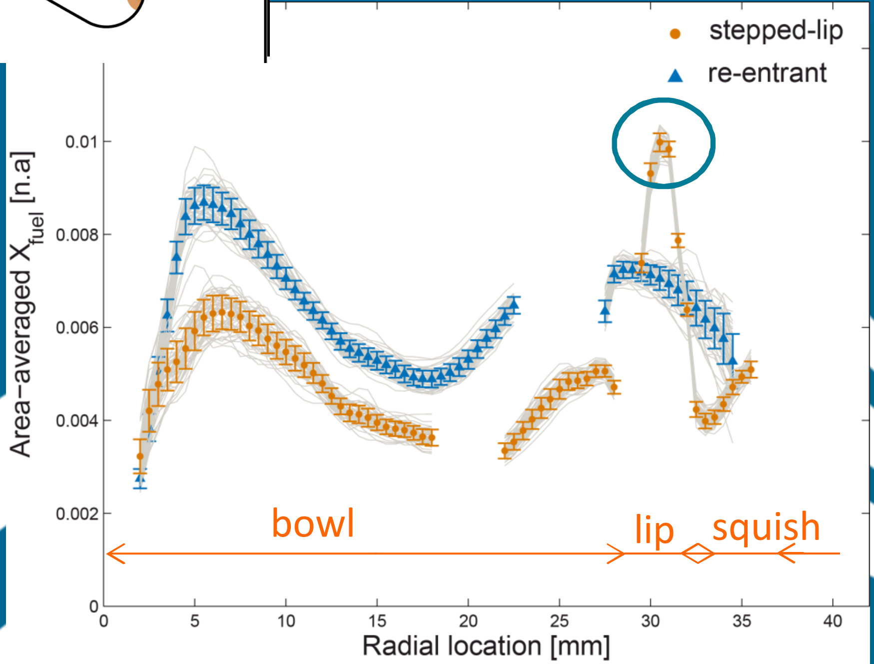
High $\chi_{fuel,d}$ is observed in lip region!

High $\chi_{fuel,d}$ observed in lip region implies better air utilization with stepped-lip piston geometry.



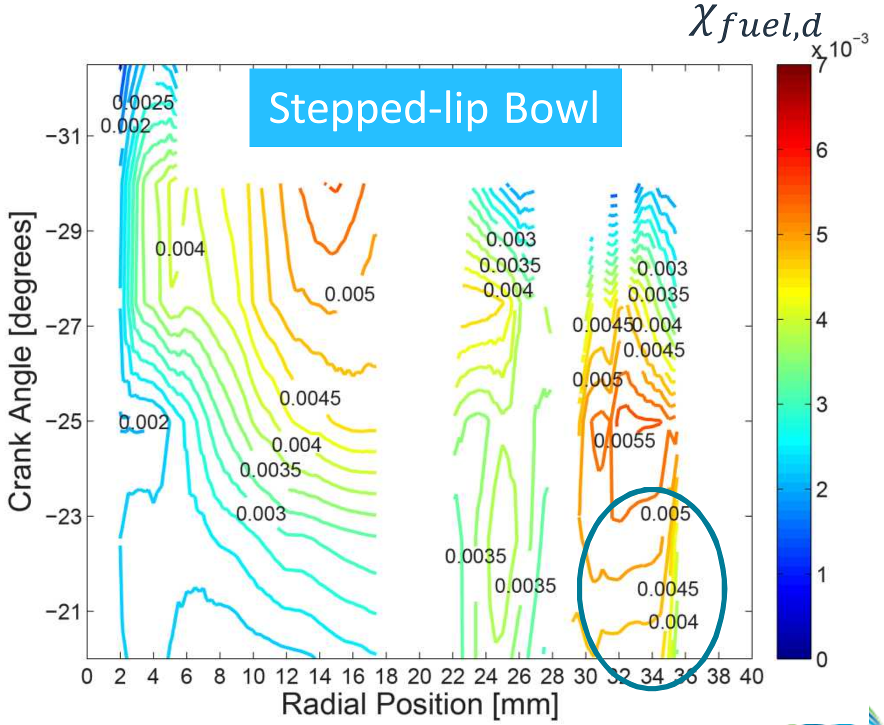


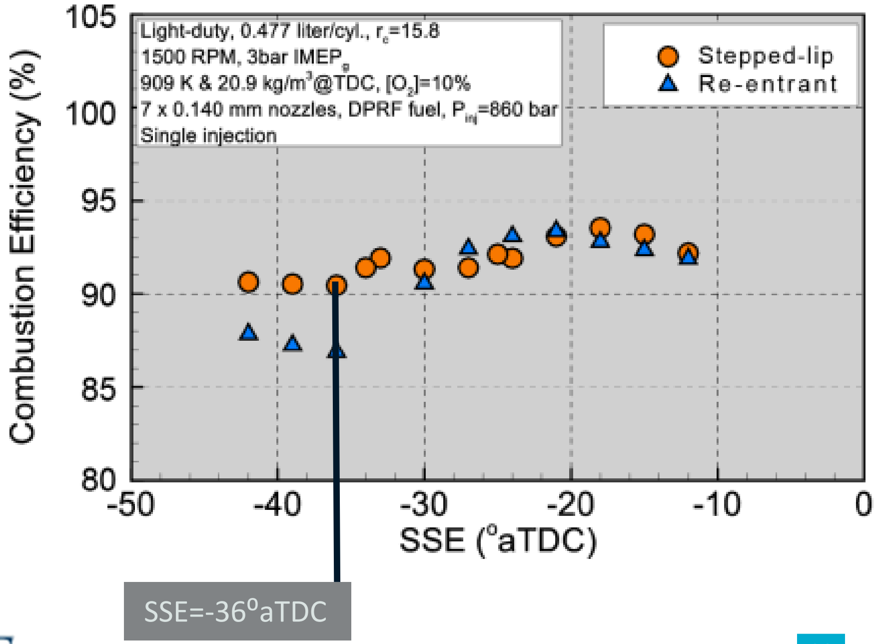
Area-averaged $\chi_{fuel,d}$



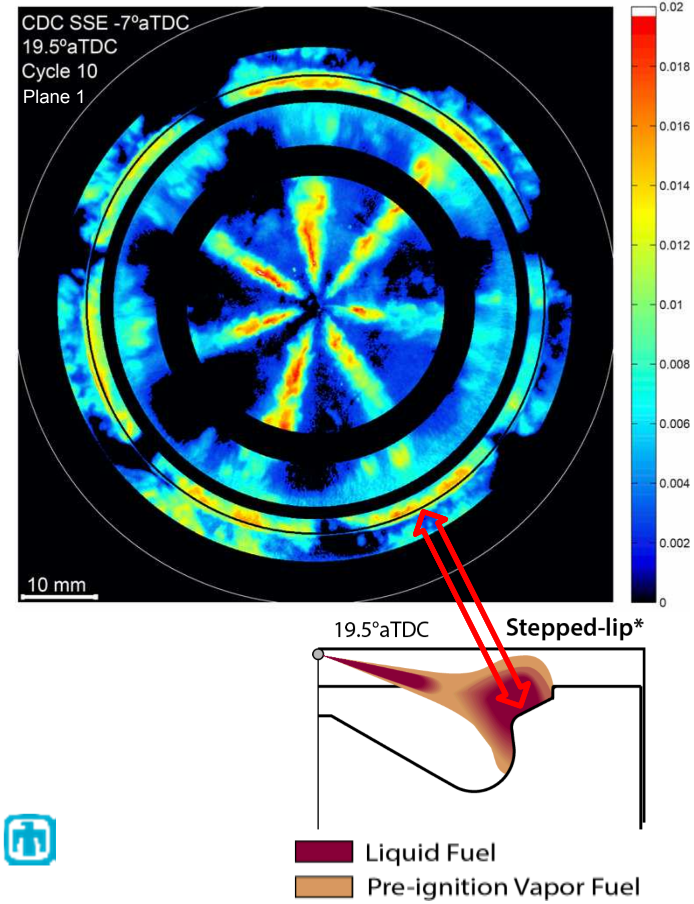
Error bar marks ±σ out of 50 realizations

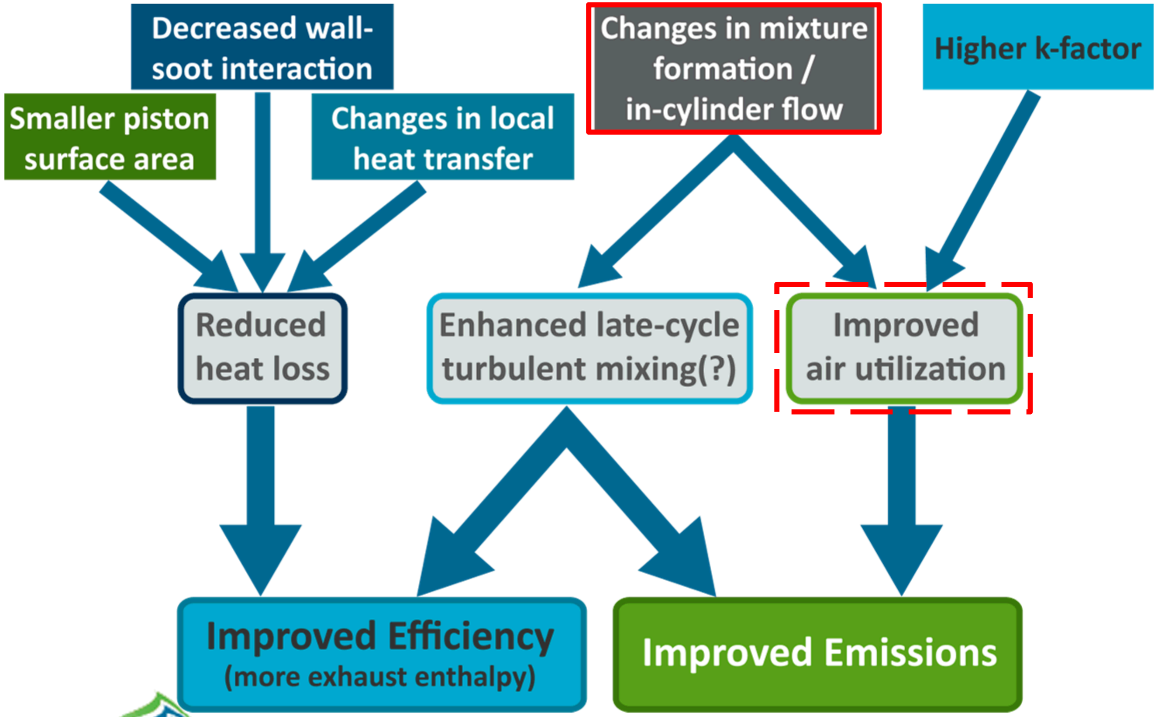
Conclusion - Stepped-lip bowl exhibits less squish area. In EGR-diluted LTC region, this geometry results in less CO from squish-region lean mixtures. Therefore, higher combustion efficiency.





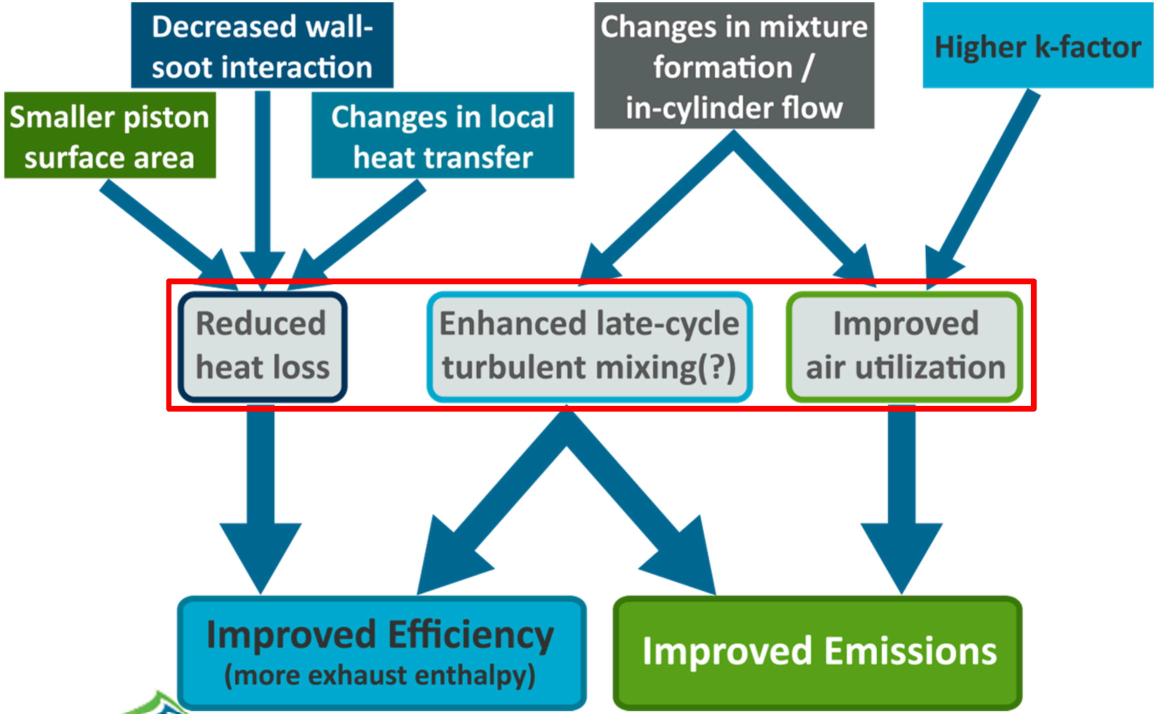
Conclusion - Stepped-lip geometry results in localized high fuel concentration on lip shoulder, which implies better air utilization.





Future work: Understanding the geometry-induced mechanisms for increased heat release rates and higher efficiency.

- Optical experiments: SNL
  - High-speed soot natural luminosity imaging
- Computational studies: UW
  - Bowl geometry, fuel injection, and combustion impact on in-cylinder flow
  - Speed / load /spray targeting sensitivities



Acknowledgement

- Federico Perini, Professor Rolf Reitz, UW-Madison ERC
- Tim Gilbertson, R&D Technologist, Sandia

Thank you for your attention!

Questions?

PLIF: computation of fuel concentrations

- $\chi_{fuel,d} = \chi_{fuel,cal} \frac{S_d}{S_{cal}} \frac{E_{cal}}{E_d} \frac{T_d}{T_{cal}} \frac{P_{cal}}{P_d} \frac{\sigma\eta(T_{cal})}{\sigma\eta(T_d)}$
  - S : background-subtracted, distortion-corrected image intensity
  - E : measured laser pulse energy
  - T : bulk gas temperature from GT-Power model
  - P : cylinder pressure from GT-Power model
  - $\sigma\eta$: product of absorption cross section and quantum yield; function of temperature alone

- Calibration with homogeneous mixture of known concentration ($\chi_{fuel,cal}$)
  - "Flat-field" correction

- $\sigma\eta(T)$ is determined with separate measurements and analyses

PLIF temperature calibration

- $\sigma\eta(T)$ determined from flat-field images taken at various crank angles and for various intake temperatures
- Upper limit of possible flat-field fuel concentrations limited by wall-wetting
  - $\phi_{ff} \approx 0.3$
- Comparison with previous temperature calibration
  - Coefficients between 14-18% higher than previously determined values
  - The arbitrary normalization of the calibration curve is responsible for the majority of this discrepancy
- Future plans include expanded calibration dataset