SAND2016-1293C

Piston Geometry Effects on Emissions and Fuel Efficiency in a Light-Duty Diesel Engine

Kan Zha[a], Stephen Busch[a], Federico Perini[b], Rolf D. Reitz[b]

[a] Sandia National Laboratories
[b] University of Wisconsin-Madison

Abstract

In direct-injection light-duty swirl-supported diesel engines, stronger spray-wall interactions are expected when using re-entrant piston bowl geometry comparing with heavy-duty diesel engines which are usually operating with open-bowl-shaped piston under low swirling flow conditions. Small-bore light-duty diesel engines are expected to experience more liquid-phase impingement and the re-direction of jet momentum by piston surfaces. Moreover, stronger swirl will induce cross-flow near TDC and the squish-swirl interaction complicate the design of bowl geometry for light-duty swirl-supported diesel engines. Previous metallic engine studies have reported that the open-bowl-shaped (called stepped-lip) piston exhibits benefits both in emissions and fuel efficiency. The experimental work presented here is the scoping study to evaluate the performance of the two different piston geometries (conventional re-entrant and stepped-lip) in terms of efficiency and pollutant emissions. The results of this study will guide upcoming optical investigations to provide insight about differences in mixture formation behavior with these two pistons. Motivation is to identify the points of interest in which piston geometry effects are pronounced in terms of emissions and fuel efficiency under low speed, low-temperature combustion (LTC) and conventional combustion regimes. Results show that in single-injection, EGR-diluted LTC regime, piston geometry has both thermodynamic and combustion impacts. In conventional combustion regime (part-load), impact of piston geometry is primarily on thermodynamics.

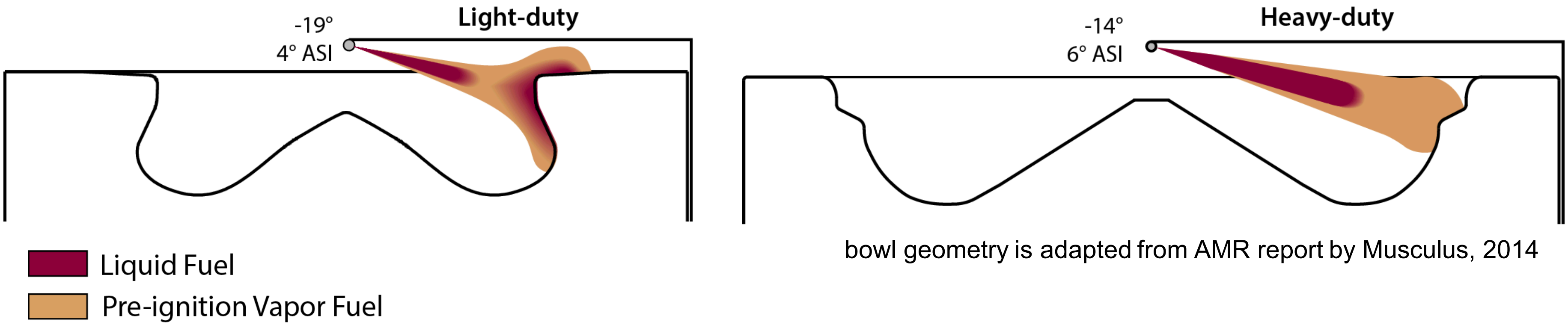
This work is made possible through the support from the Office of Vehicle Technologies: Gurpreet Singh / Leo Breton and General Motors: Alok Warey; Ford: Eric Kurtz (principal technical contact)

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

Outline

- Motivation
- Objectives of current study and experimental setup
- Pistons for comparison
- Results
  - Operating conditions for low-speed, low-load (3bar) EGR-diluted LTC conditions.
  - Operating conditions for low-speed, part-load (9bar) conventional combustion conditions.
- Summary
- Future Work

Motivation: why piston geometry effect is of great importance to light-duty diesel engines?

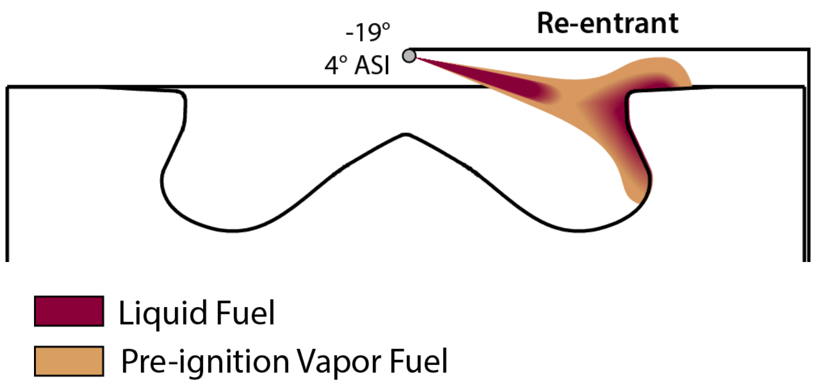


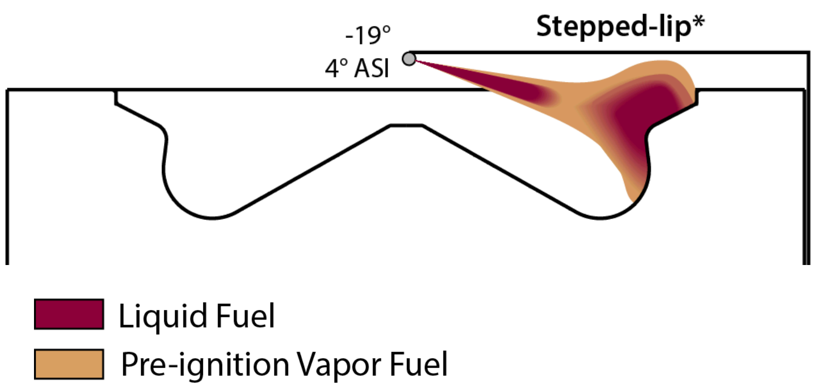
bowl geometry is adapted from AMR report by Musculus, 2014

- Light-duty Diesel engine with re-entrant piston has
  - smaller bore size (by ~ 20%) & higher squish-to-bowl ratio, therefore…
  - stronger spray-wall interactions, including liquid phase impingement and re-direction of jet momentum by the piston surfaces
  - stronger swirl which creates a cross-flow near TDC
  - squish-swirl interaction which results in complicated mean flow topologies and angular momentum distributions.

Objectives of current study and experimental setup

Research engine	Single-cylinder
Cycle	4-stroke
Intake/Exhaust Valves	2/2
Bore	82.0 mm
Stroke	90.4 mm
Displacement per cylinder	0.477 liters
Conn. Rod length	166.7 mm
Squish height	1.4 mm
Swirl ratio (Ricardo)	2.2
Compression ratio	15.8
Intake Valve Open (IVO)	-359 °CA
Intake Valve Close (IVC)	-152 °CA
Exhaust Valve Open (EVO)	132 °CA
Exhaust Valve Close (EVC)	360 °CA
Fuel	$C_{16}H_{34}$

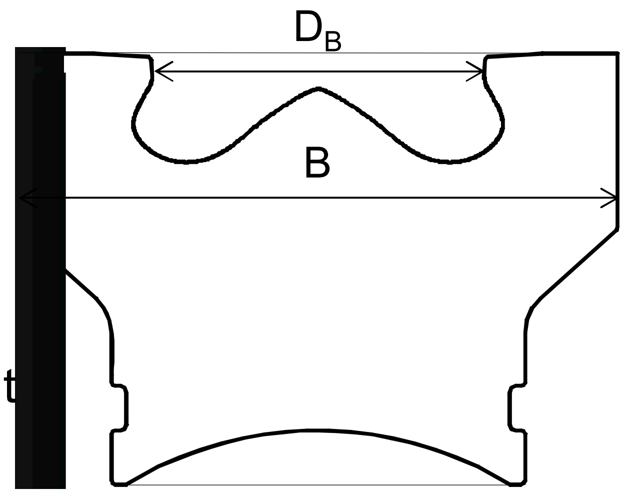




* Kurtz, E. and Styron, J., "An Assessment of Two Piston Bowl Concepts in a Medium-Duty Diesel Engine," *SAE Int. J. Engines* 5(2):344-352, 2012, doi:10.4271/2012-01-0423.

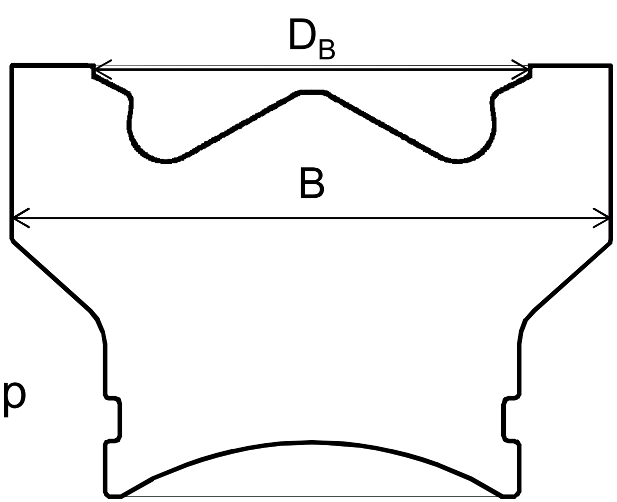
Pistons for comparison

- Two piston bowl geometries with the same bowl volume available for baseline tests.



Re-entrant

- Titanium piston (no valve cut-outs)
- Squish height (TDC) = 1.37 mm (warm)
- Compression ratio = 15.8
- Bowl to bore ratio: $D_B/B=0.55$
- Injector washer is modified for desired spray targeting.



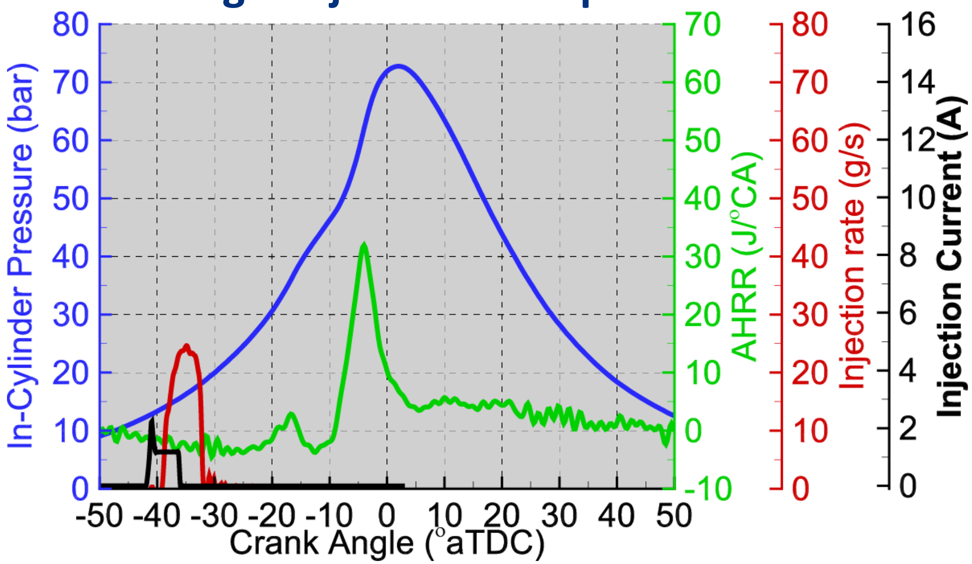
Stepped-lip

- Titanium piston (no valve cut-outs)
- Squish height (TDC) = 1.35 mm (warm)
- Compression ratio = 15.8
- Bowl to bore ratio: $D_B/B=0.73$
- Injector washer is modified for desired spray targeting.

LTC operating condition

Engine speed	1500 rpm
Intake charge mole fractions	O_2 : 10% CO_2 : 9% N_2 : 81%
Constant intake mass flow rate	8.936 g/s
Intake temperature	99 ^oC
Intake pressure	~ 1.5 bar
$IMEP_g$	3.0 bar
Injected fuel	~ 11 mg/str
Injection pressure	860 bar
SSE sweep timings	-42~-12 CAD ^{o}aTDC
Injection duration	~4.2 CAD
Swirl ratio (Ricardo)	2.2
TDC density	20.9 kg/m^3
TDC temperature	909 K
Fuel	$C_{16}H_{34}$

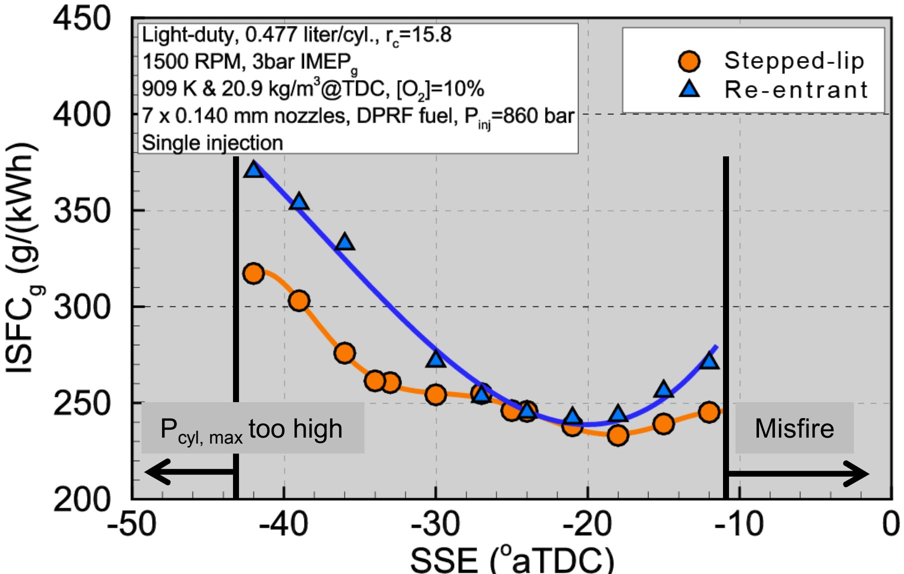
- 0^oCA are referenced to the firing TDC
- Engine is skip-fired: 1 fired + 4 motored
- N_2 and CO_2 added to intake air to achieve target X_{O_2}

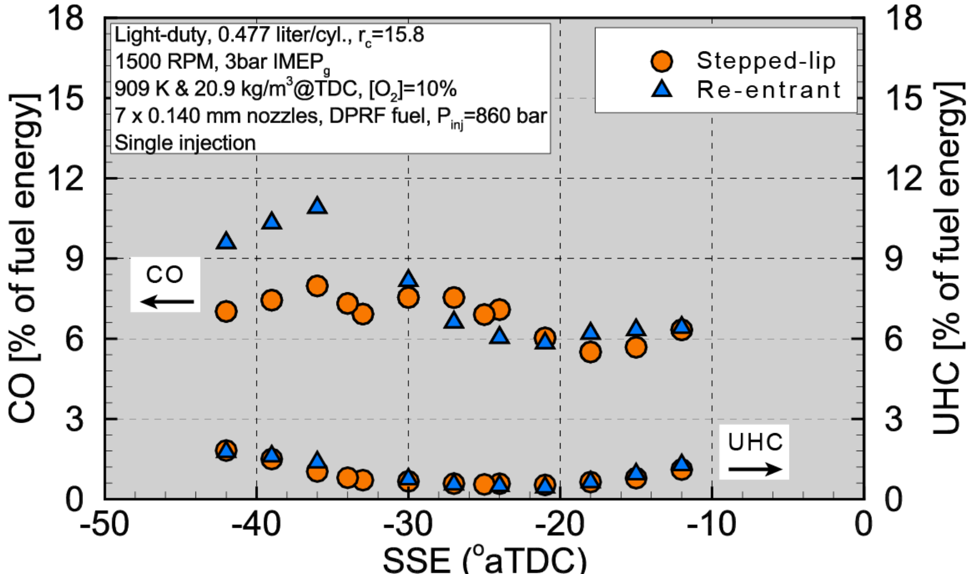


50 firing cycles

Fuel efficiency improvement is observed with stepped-lip piston geometry under single-injection, EGR-diluted LTC conditions.

- At MBT timing, no significant difference in indicated fuel efficiency is observed between two pistons. (3% uncertainties in $IMEP_g$, 0.9% uncertainties of HDA).
- Stepped-lip piston has fuel efficiency advantage both at early-injection and late-injection timings.
- With early-injection timings, lower CO emission is observed with stepped-lip piston suggesting higher combustion efficiency.
- UHC emissions are similar for both piston geometries.



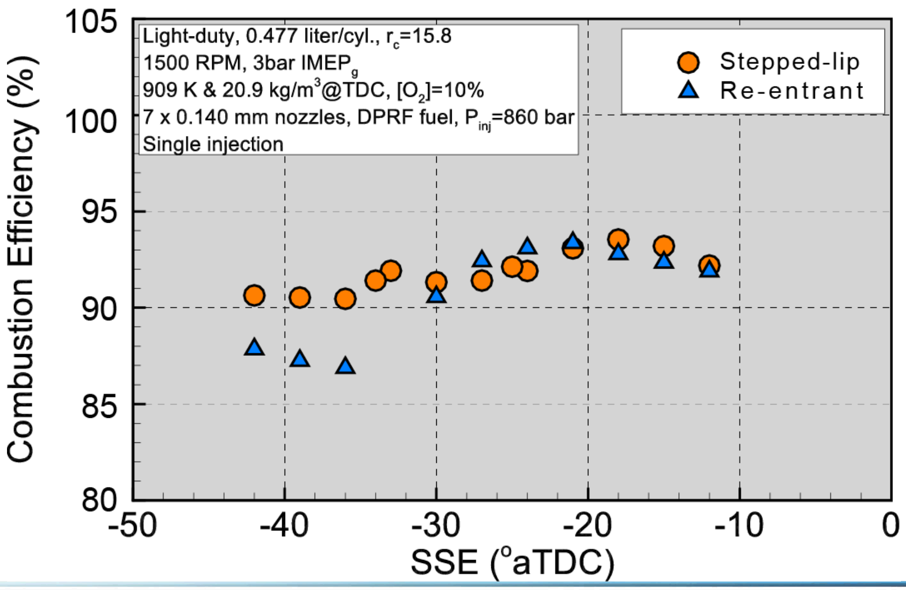


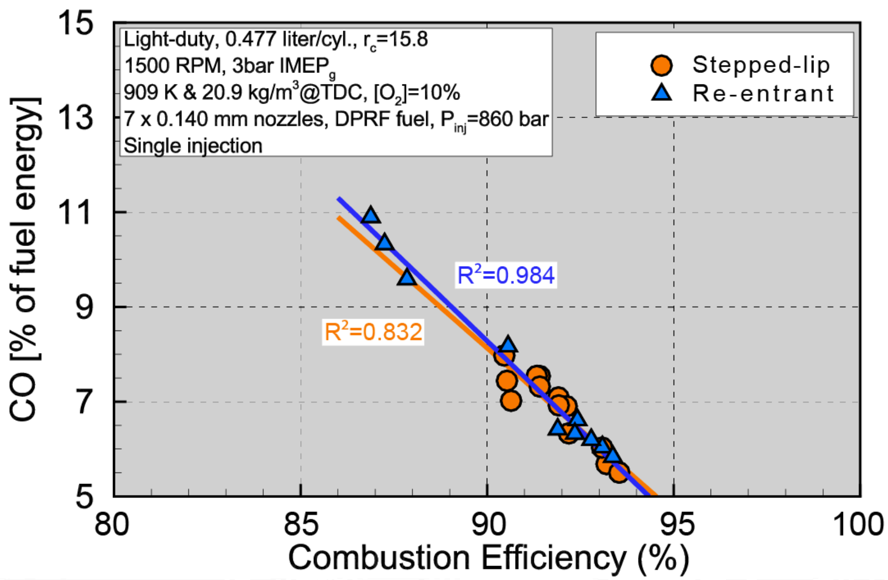
Stepped-lip piston yields in higher combustion efficiency (η_{comb}) with early-injection, EGR-diluted LTC conditions.

Combustion efficiency (η_{comb}) is defined as:

$$\eta_{comb} = 100 - 100 \times \frac{m_{UHC} \times LHV_f + m_{CO} \times LHV_{CO} + +m_{H_2} \times LHV_{H_2}}{m_f \times LHV_f}$$

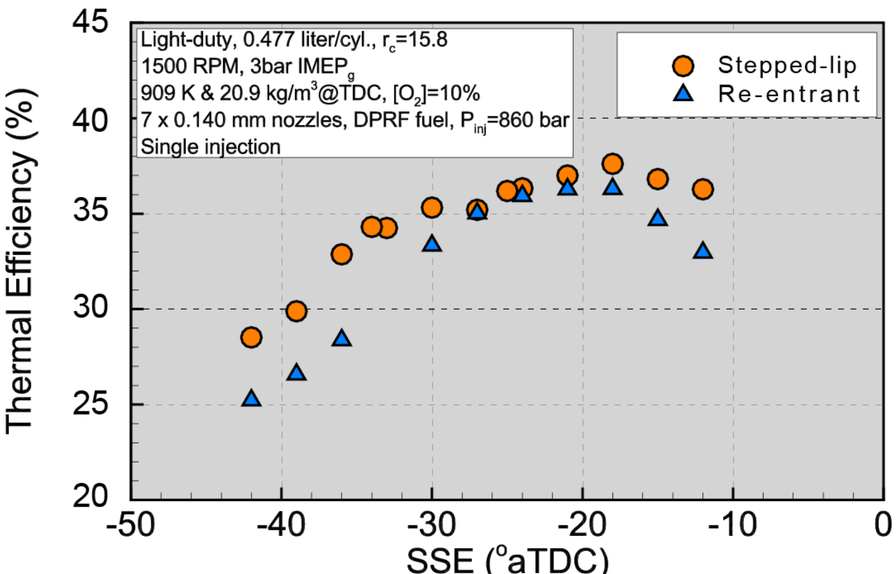
- Different trends in combustion efficiency are observed with two piston geometries.
- Maximum combustion efficiency location for both piston geometries are similar.
- CO emission has strong linear correlation with combustion efficiency.

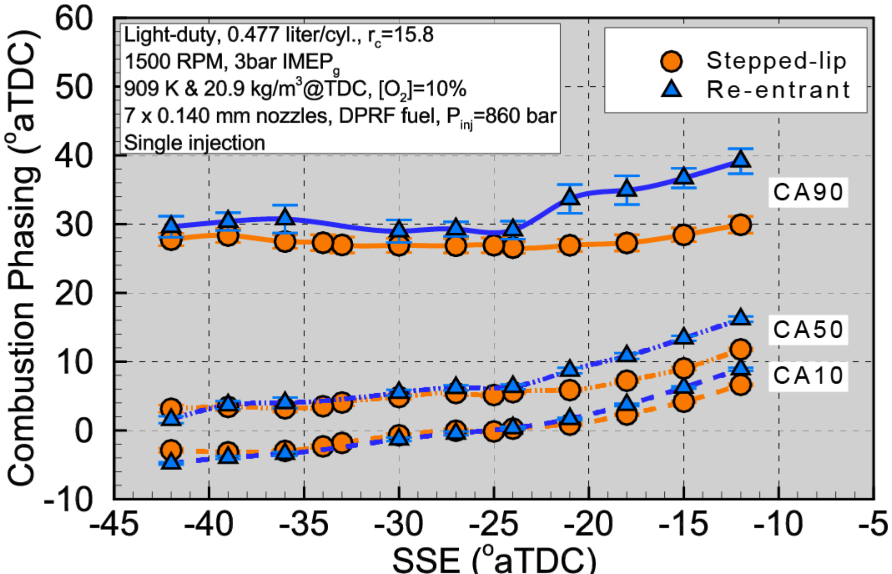




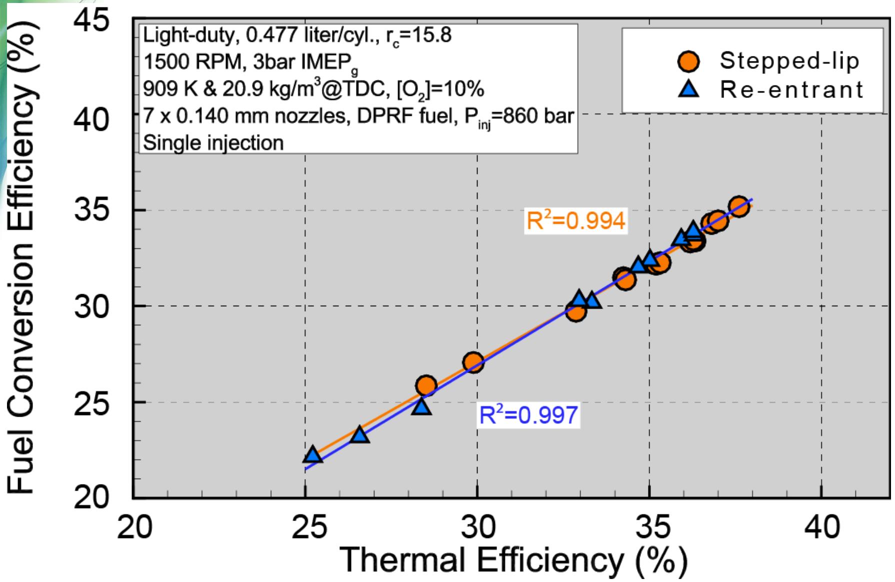
Stepped-lip piston also exhibits thermal efficiency (η_{th}) advantage both at early-injection and late-injection timings.

- The trends in thermal efficiency (η_{th}) is a trade-off between combustion phasing (CA50), rate of heat release and heat transfer losses.
- At early-injection timings, slightly higher η_{th} for stepped-lip piston may be explained by its higher rate of heat release and less heat transfer losses.
- At intermediate injection timings, η_{th} is similar for both piston geometries.
- At late-injection timings, combustion phasing (CA50) for stepped-lip piston is more advanced suggesting gaining in expansion ratio.

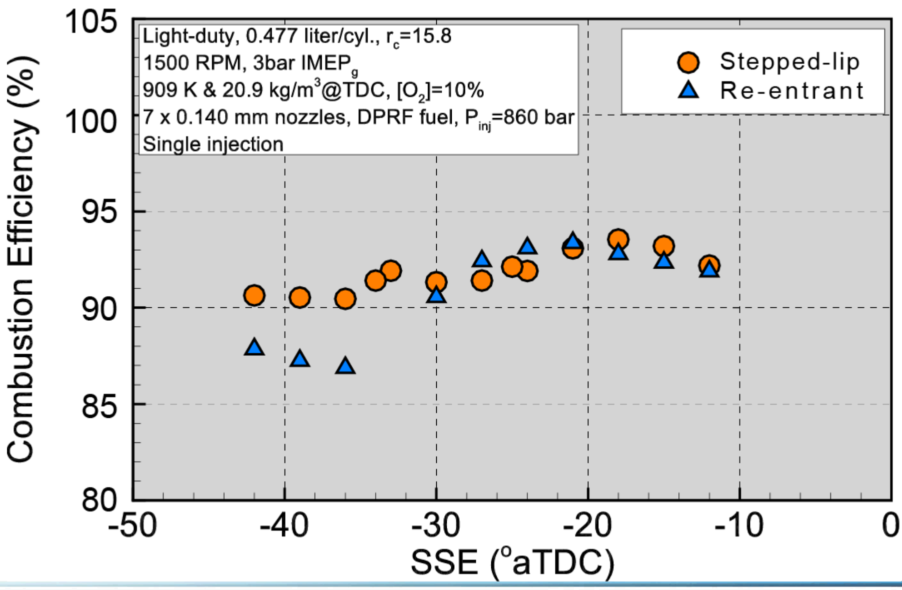


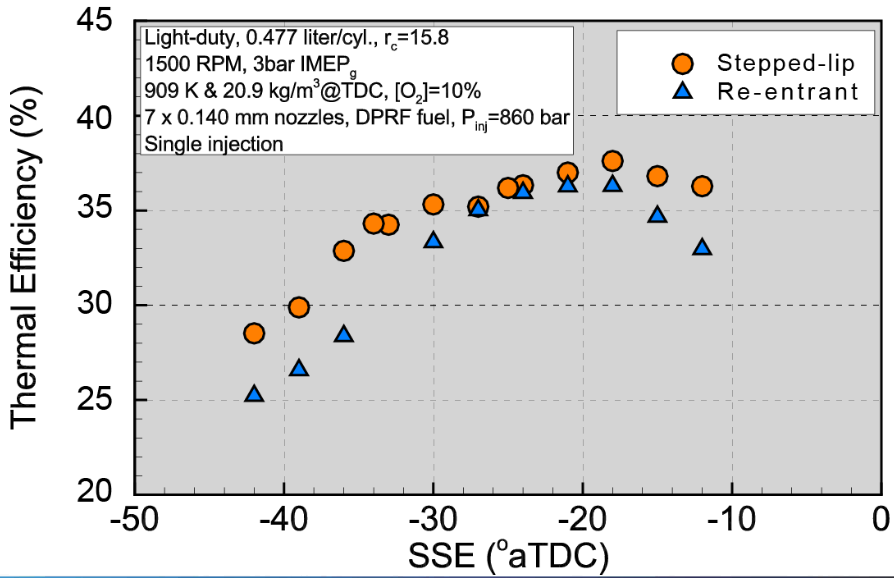


In single-injection, EGR-diluted LTC regime, piston geometry has both thermodynamic and combustion impacts.



- In single-injection, EGR-diluted LTC conditions regime, the trend of ISFC is still dominated by thermal efficiency (η_{th}).
- At early-injection timings, piston geometry impacts on both thermodynamics and combustion are observed.
- At late-injection timings, piston geometry impact on thermodynamics is observed.



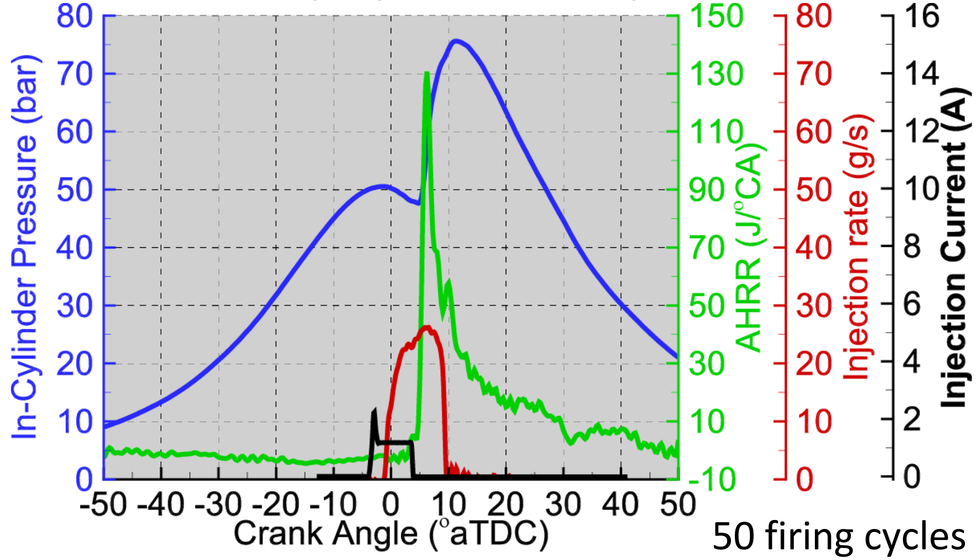


Conventional operating conditions

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	-19~2 CADºaTDC
Energizing dwell	1200 μs
Main inj. duration	~6.5 CAD
Swirl ratio (Ricardo)	2.2
TDC density	21.8 kg/m³
TDC temperature	925 K

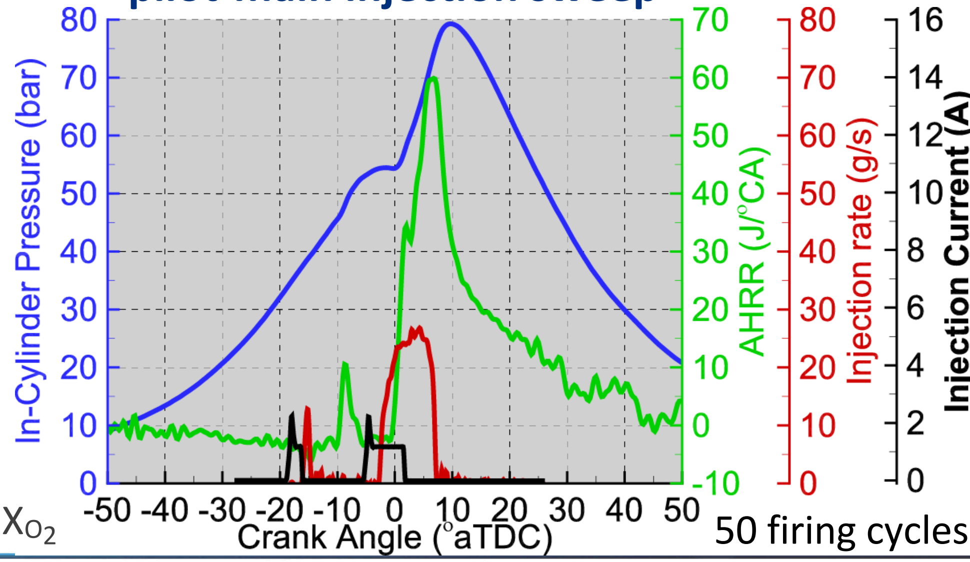
- 0ºCA are referenced to the firing TDC
- Engine is skip-fired: 1 fired + 4 motored
- N_2 and CO_2 added to intake air to achieve target X_{O_2}

main-only injection sweep



50 firing cycles

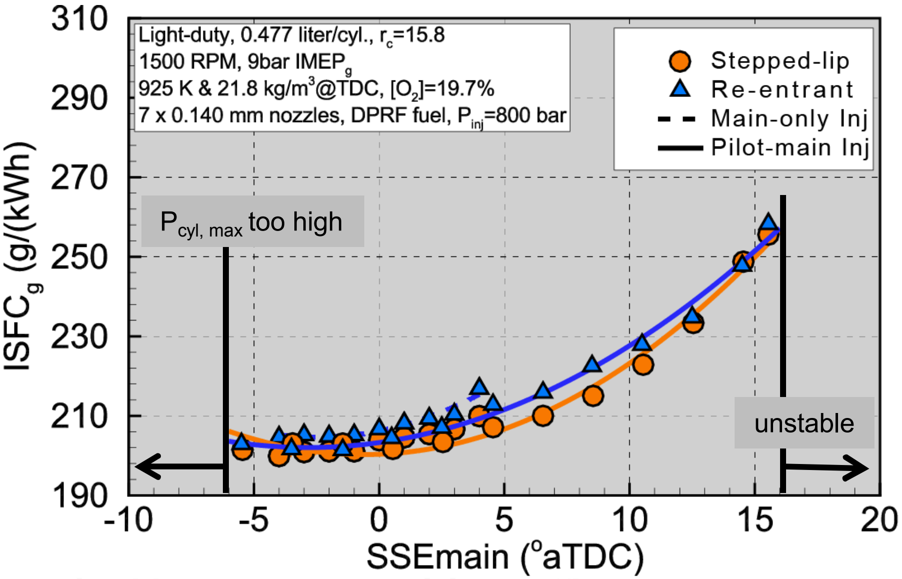
pilot-main injection sweep

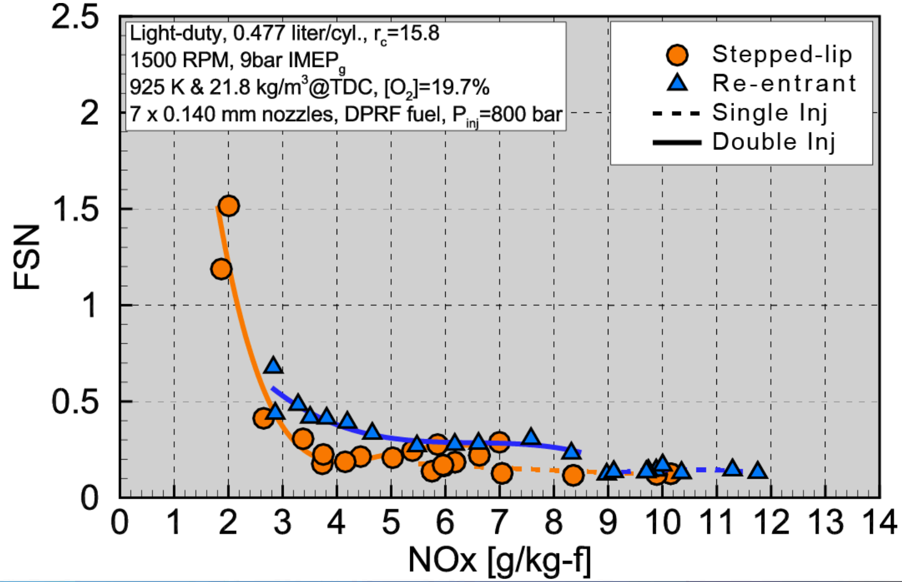


50 firing cycles

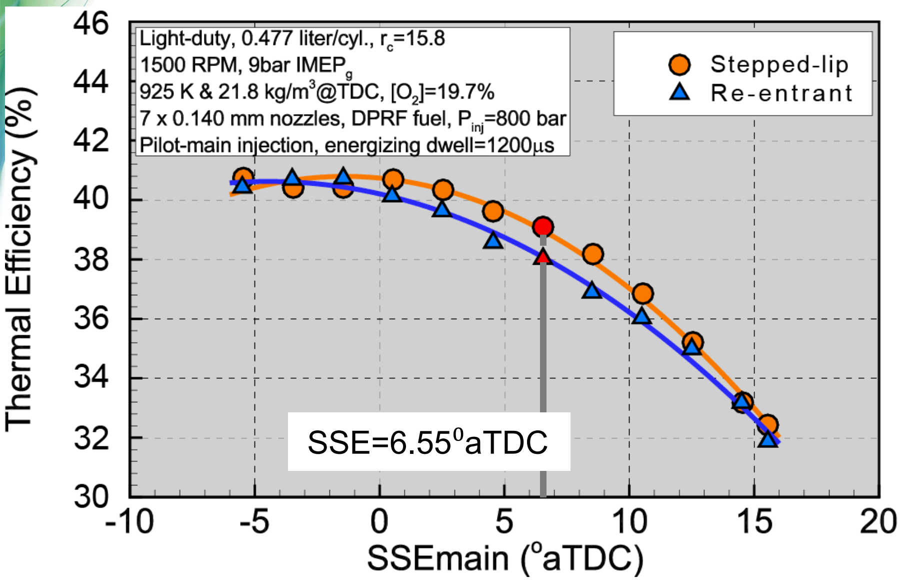
In conventional part-load regime (9bar), piston geometry effect is more pronounced in fuel efficiency and emissions when pilot-main injection strategy is utilized.

- Pilot-main injection strategy is used to broaden injection sweeping range.
- With pilot-main injection, lower NOx emission is observed due to late-injection into combustion charge with decreased temperature.
- Better $ISFC_g$ is observed with stepped-lip piston geometry for both main-only and pilot-main injection strategies. (0.5% uncertainties in $IMEP_g$, 0.5% uncertainties of HDA).
- With pilot-main injection strategy, $ISFC_g$ with stepped-lip piston is improved by 2% at MBT timings.

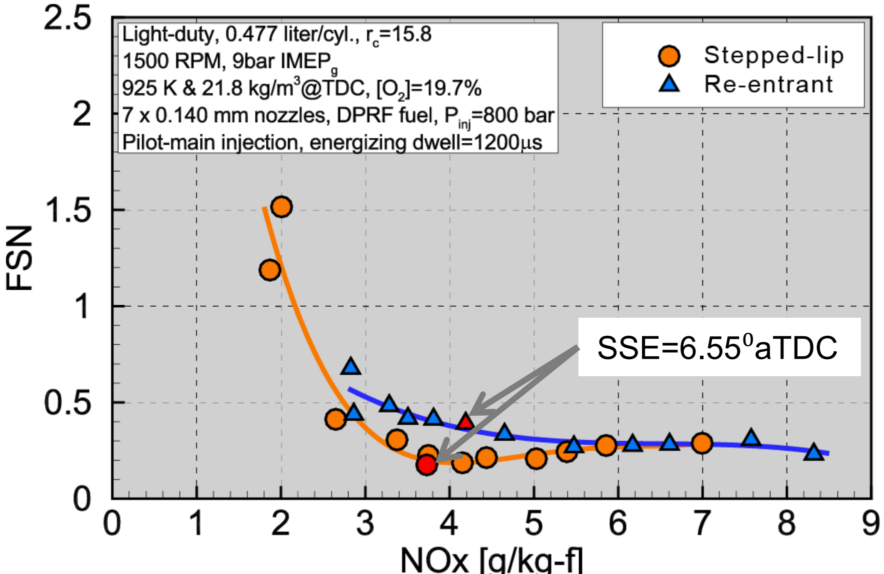


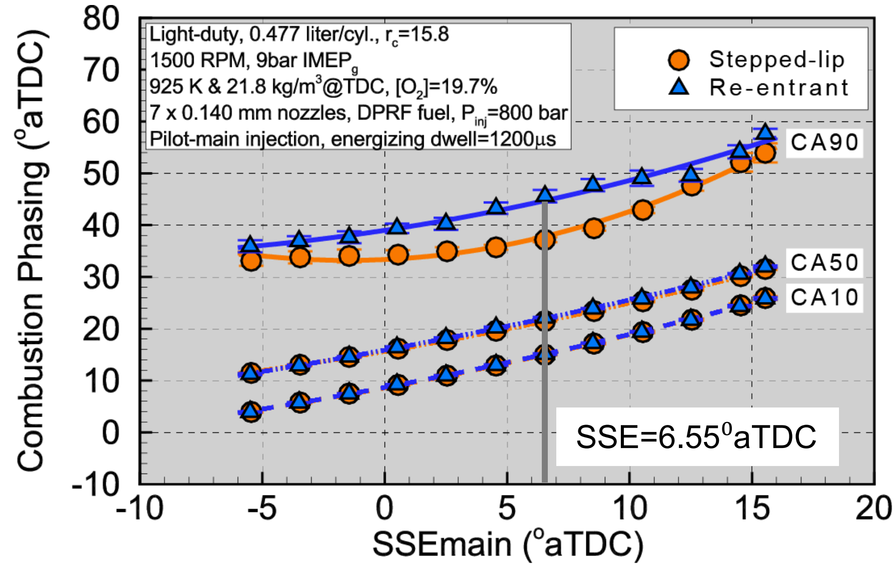


Stepped-lip piston geometry exhibits both fuel efficiency and emission benefits with intermediate pilot-main injection strategy.

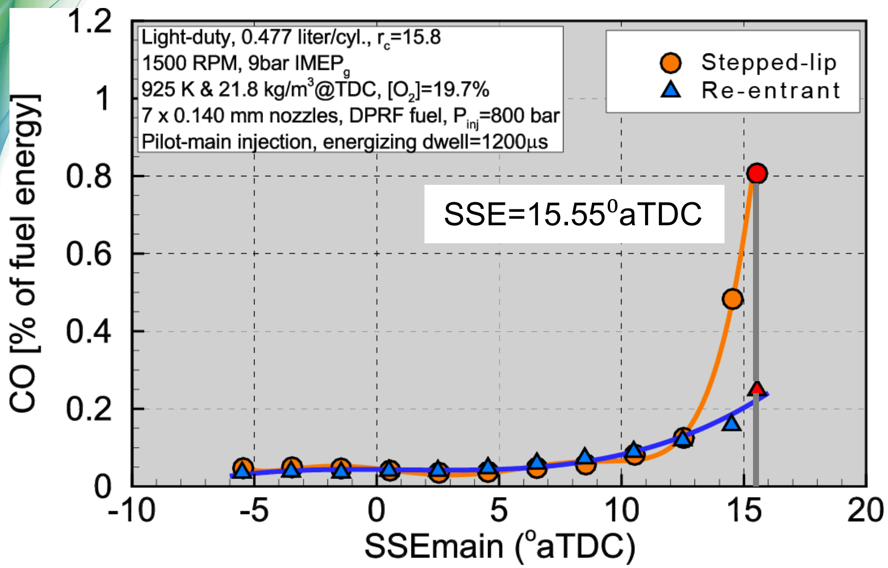


- 2.8% increase in thermal efficiency.
- Similar combustion efficiency > 99%.
- Similar combustion phasing (CA50).
- Shorter late-combustion duration CA90-CA50, by 7.7 CAD.
- Less soot emission, by 55%.
- Less NOx emission, by 11%.

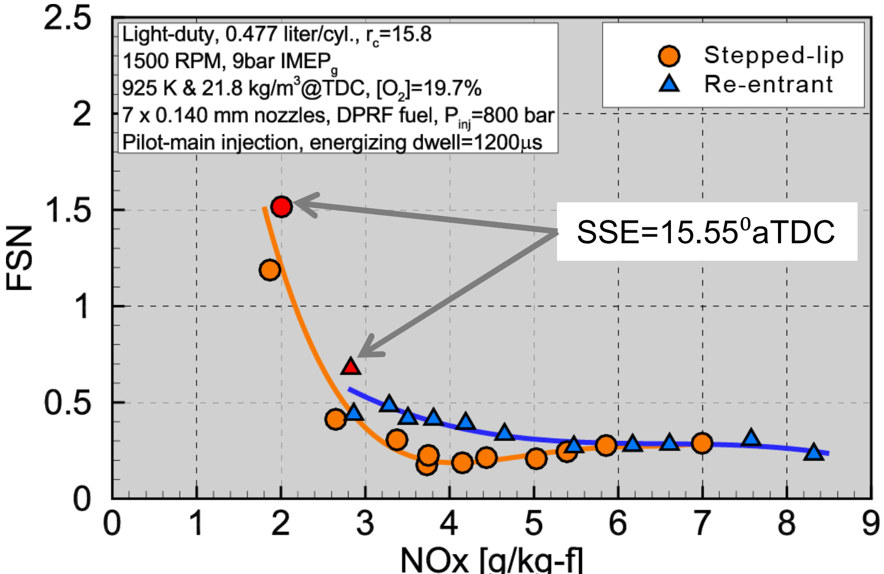


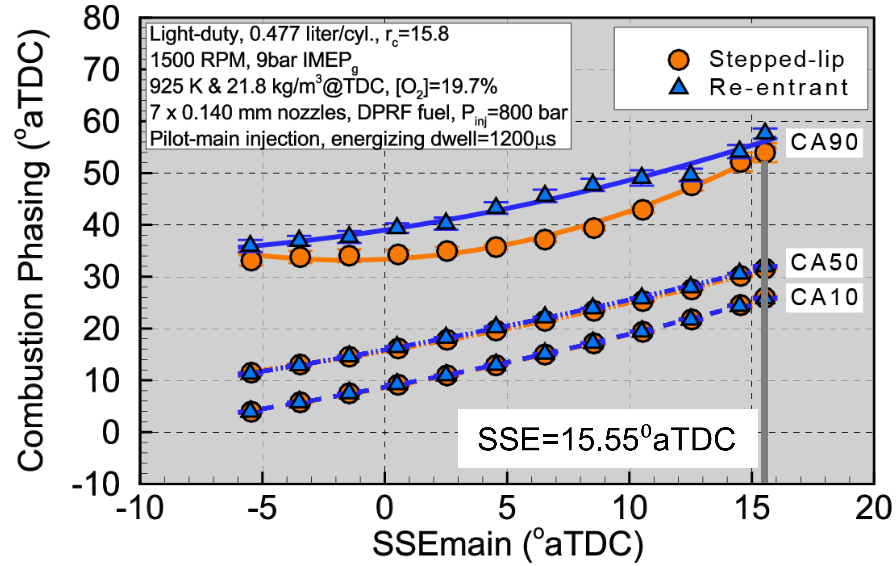


With late pilot-main injection strategy, stepped-lip geometry exhibits higher penalties in combustion efficiency (η_{comb}) and soot emissions.



- Similar thermal efficiency ≈ 0.32.
- Less combustion efficiency, by 0.7%.
- Similar combustion phasing (CA50).
- Slightly shorter late-combustion duration CA90-CA50.
- Higher soot emission, by 124%.
- Less NOx emission, by 29%.





Slide 14

SB27 Before we publish these results, we should normalize engine-out smoke emissions by engine output or fueling. I have a correlation I can give you for this.

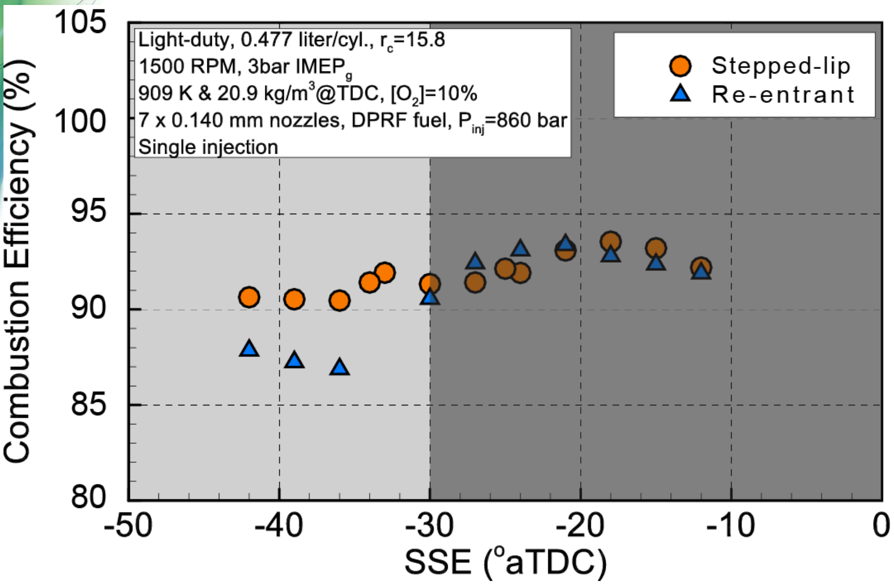
Busch, Stephen, 2/8/2016

Recap: piston geometry impacts on engine performance and emissions

- In single-injection, EGR-diluted LTC regime, piston geometry has both thermodynamics and combustion impacts.
  - At MBT timing, no significant difference in indicated fuel efficiency is observed.
  - With early-injection timings, lower CO emission is observed with stepped-lip piston suggesting higher combustion efficiency.
  - At both early-injection and late-injection timings, stepped-lip piston exhibits benefits in thermal efficiency η_{th}.
  - At intermediate injection timings, η_{th} is similar for both piston geometries.

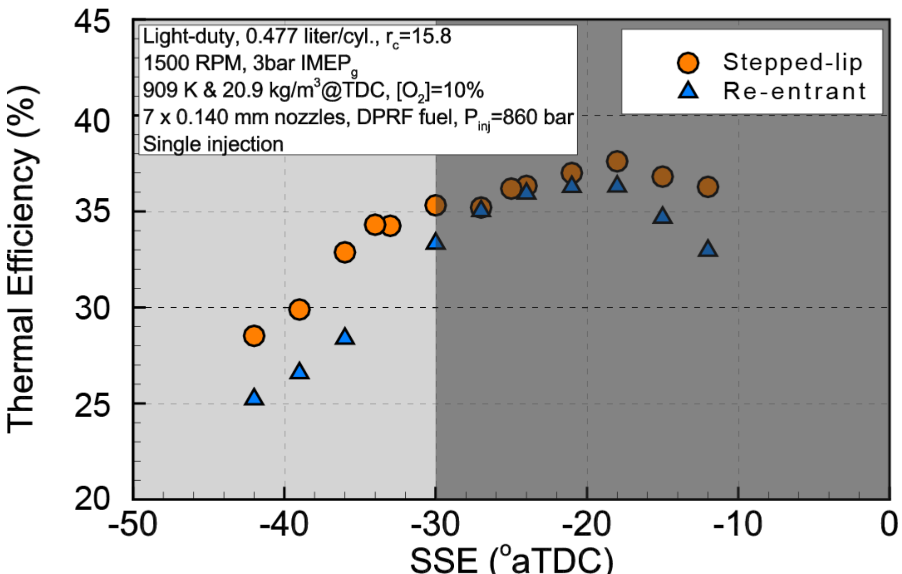
- In conventional combustion regime, impact of piston geometry is primarily on thermodynamics.
  - With intermediate pilot-main injection strategy, stepped-lip piston geometry exhibits both fuel efficiency and emission benefits.
  - The differences in thermal efficiency are attributed to significant changes in CA50-CA90.
  - With late pilot-main injection strategy, stepped-lip geometry exhibits higher penalties in combustion efficiency (η_{comb}) and soot emissions.

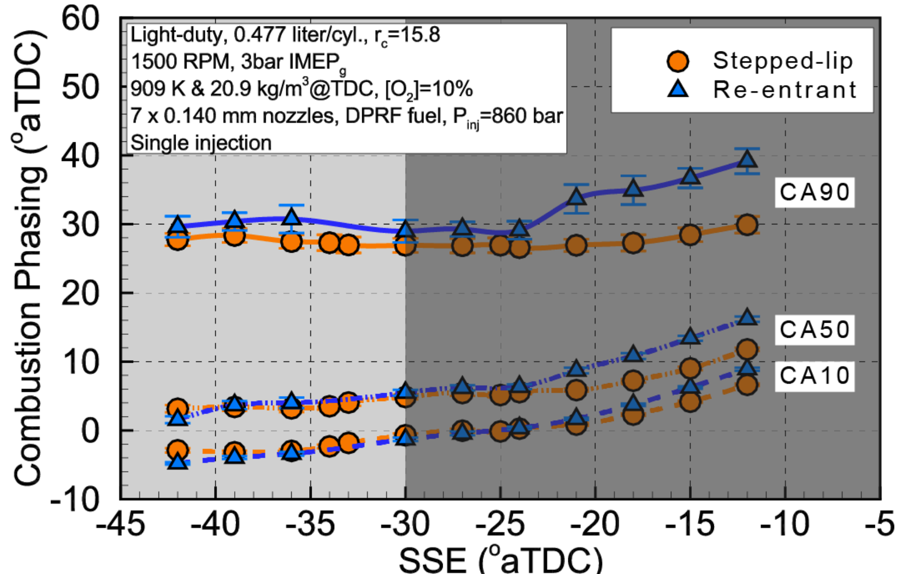
Points of interest for future optical investigations



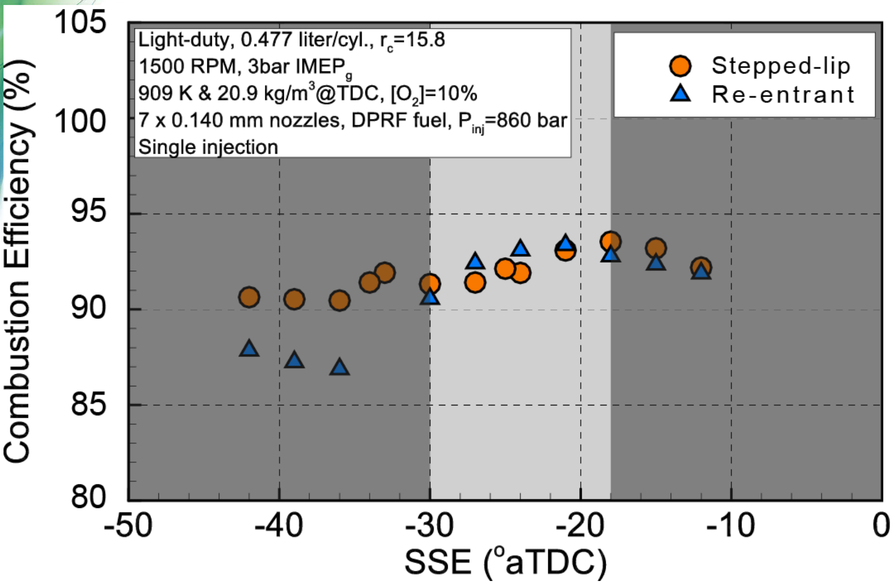
Questions to answer

1. With early injection strategies:
   - What is the difference in mixture preparation? Why stepped-lip geometry results in higher combustion efficiency?
   - With similar combustion phasing, why stepped-lip geometry induces higher thermal efficiency?
     - Heat transfer?





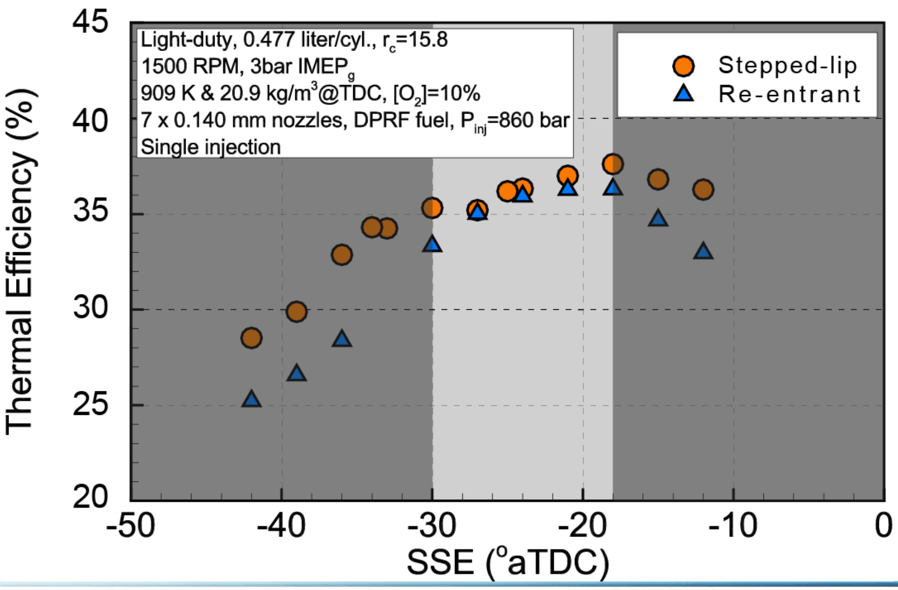
Points of interest for future optical investigations

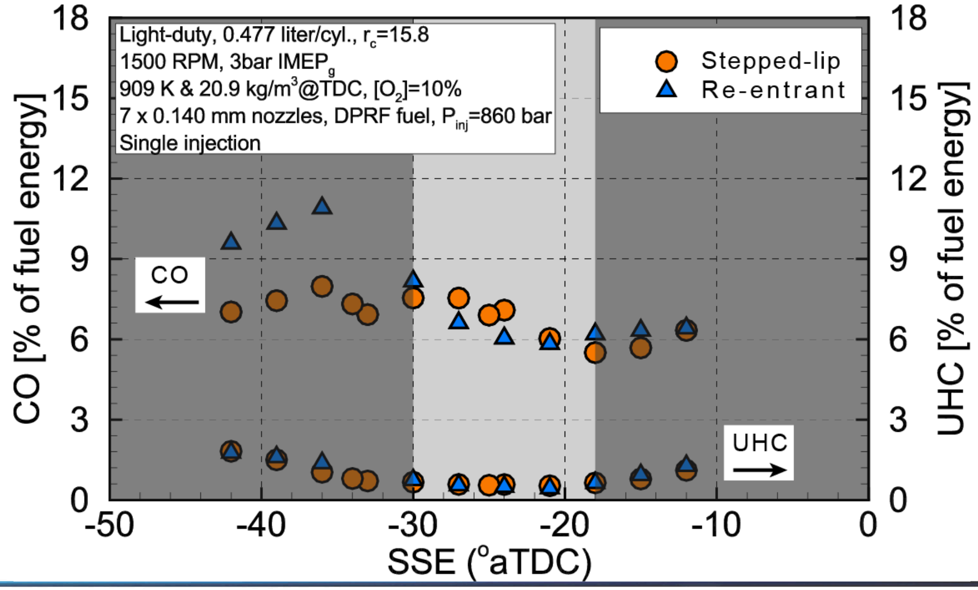


Questions to answer

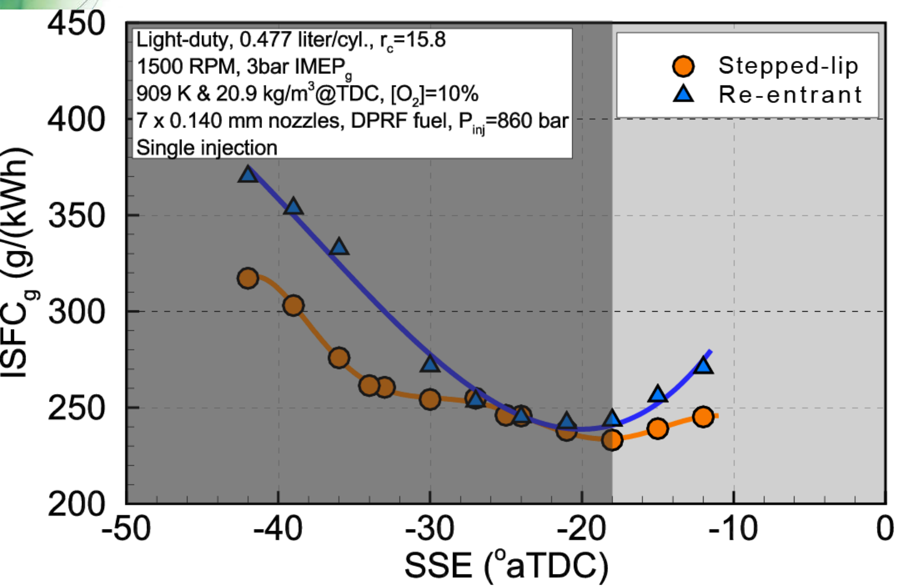
2 With intermediate injection strategies:

- Why is the effect of piston geometry not significant?





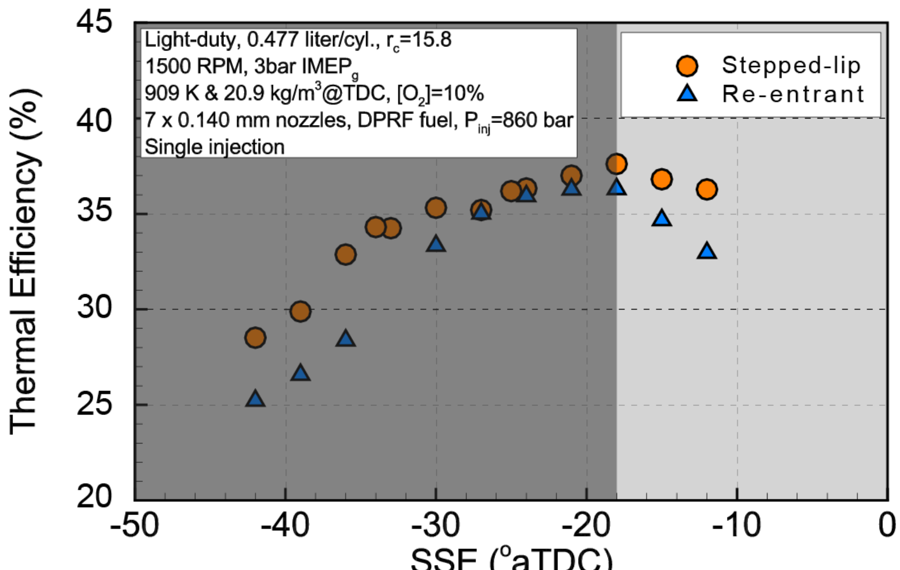
Points of interest for future optical investigations

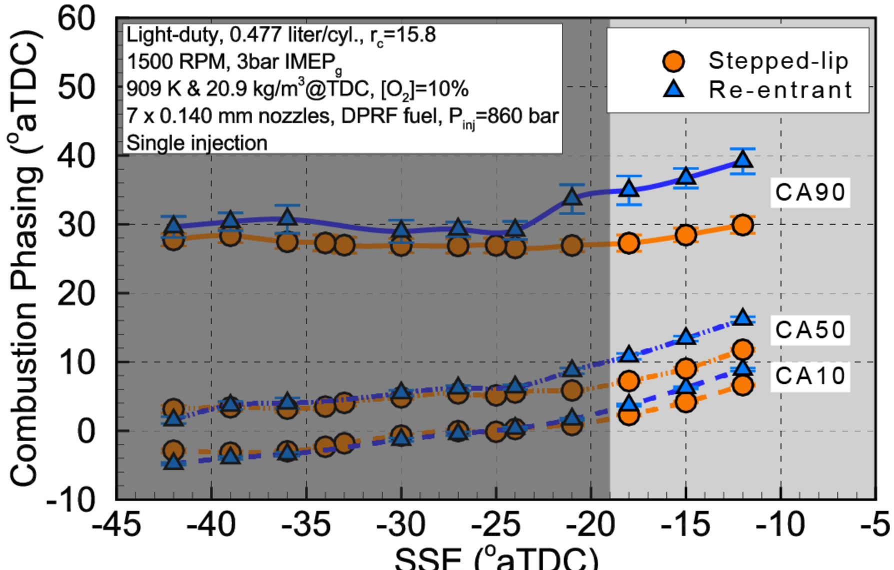


Questions to answer

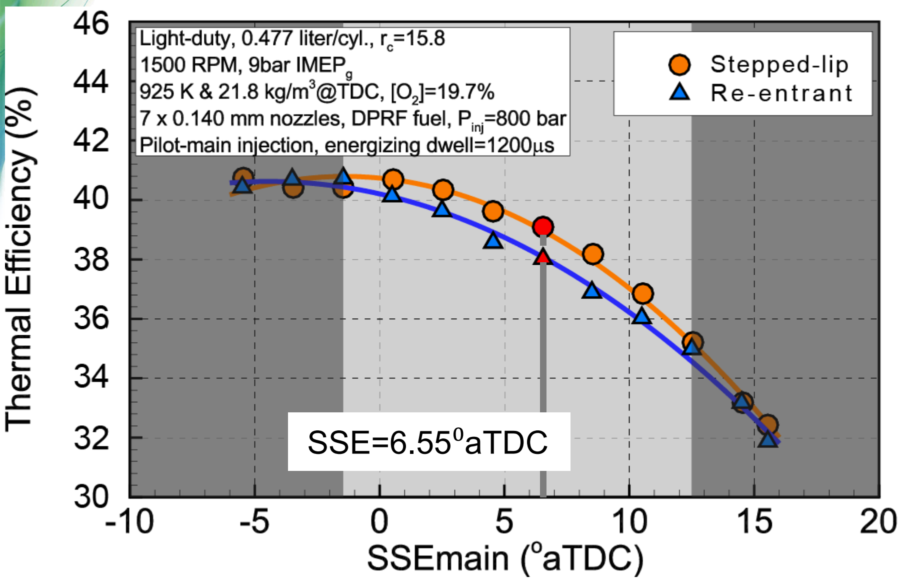
3 With late injection strategies:

- Why stepped-lip geometry results in more advanced combustion phasing and faster late burn?





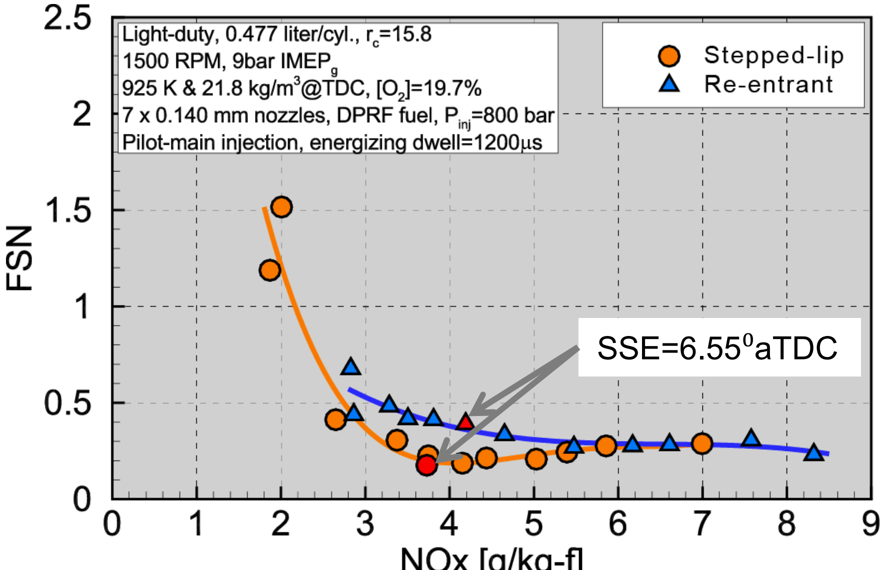
Points of interest for future optical investigations

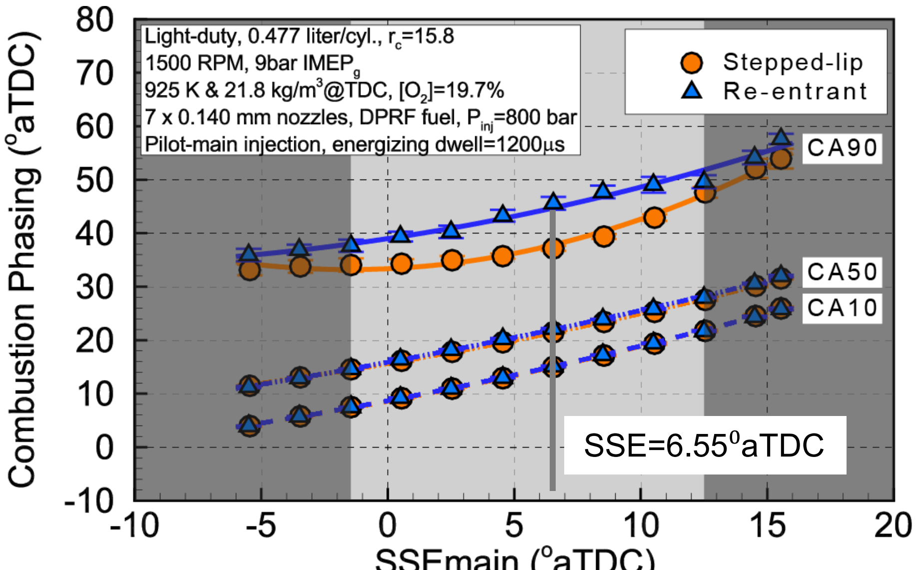


Questions to answer

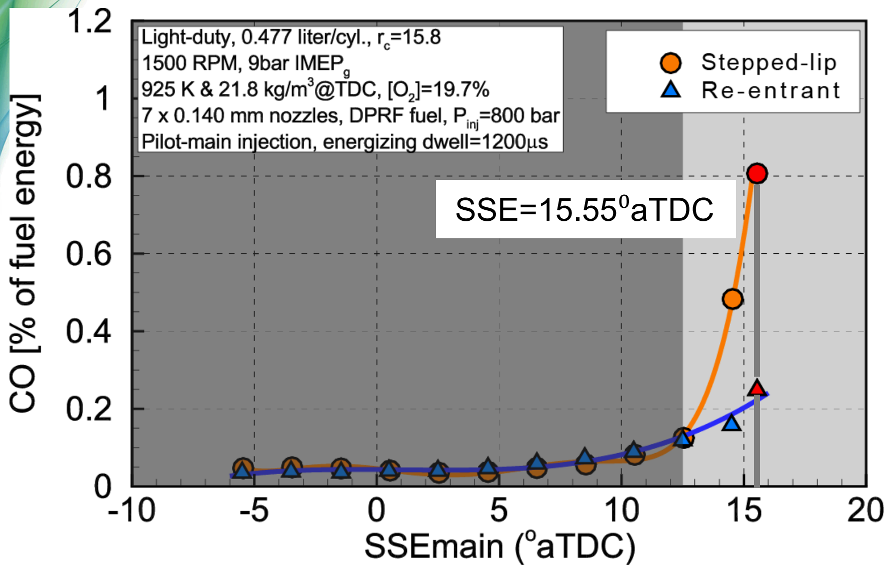
4 With intermediate pilot-main injection strategies:

- Why stepped-lip geometry induces faster late burn?
- How is the soot-NOx trade-off improved with the stepped-lip bowl?





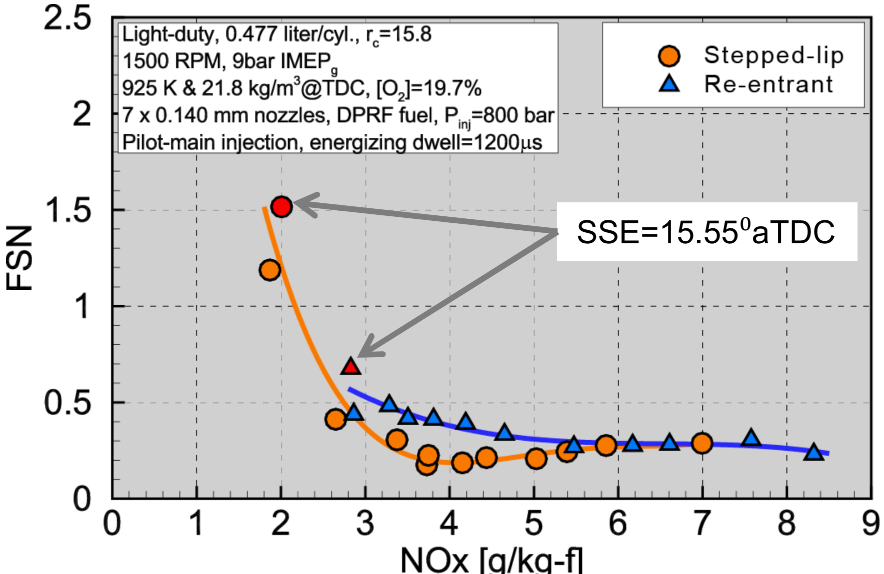
Points of interest for future optical investigations

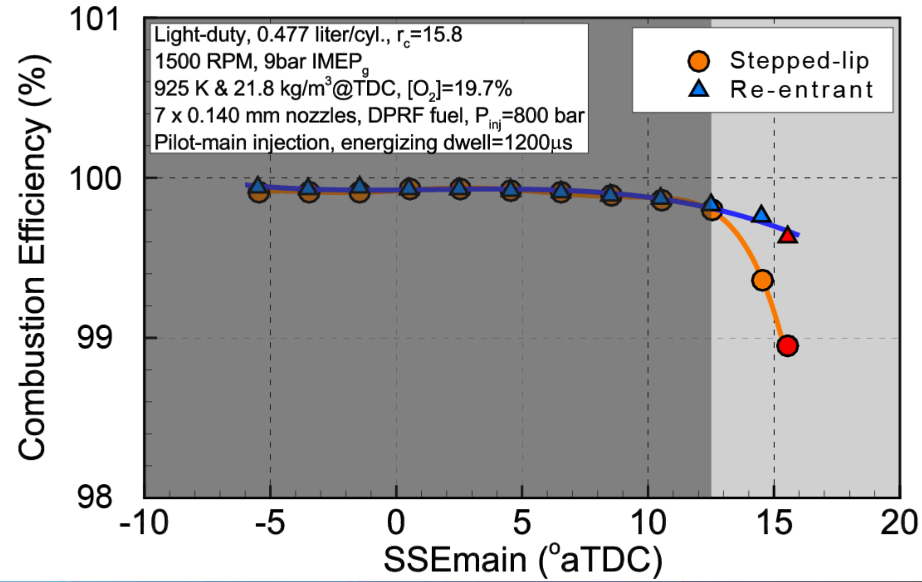


Questions to answer

5 With late pilot-main injection strategies:

- Why stepped-lip geometry induces higher penalties in soot and CO emissions?
- Why this geometry results in worse combustion efficiency?





Future investigations

- Optical measurements (SNL)
  - Fuel tracer PLIF (Feb-Mar)
    - Provide quantitative data to mixture formation behavior
    - Reference data for upcoming CFD simulations
  - Infrared fuel vapor imaging (potentially Summer)
    - Supplement PLIF results; reduced uncertainty of vapor phase penetration
  - Explore optical techniques to investigate late-cycle turbulent mixing and combustion

- CFD simulations (UW-Madison)
  - Utilize newly-developed simulation capabilities to study flow, mixture formation, and combustion for the conditions studied experimentally
  - Provide insights unavailable through experimental data alone
  - Drive development of advanced models to address shortcomings of existing ones

THANK YOU FOR YOUR ATTENTION !
QUESTIONS?