SAND2015-9009PE

Progress Report on SNL Light-Duty Diesel Engine Bowl Geometry Effects Investigation

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Sandia National Laboratories

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Progress Report Outline

- Review: current state of knowledge of bowl geometry effects on motored flow from PIV experiments and 1-D theoretical analyses
- Metal piston testing results: injection timing sweeps; stepped lip vs. conventional re-entrant bowl; emissions, efficiency data
  - LTC, light load (3bar)
  - Conventional, part load (9bar), single injection
  - Conventional, part load (9bar), pilot-main injection
- Where do we go from here?
  - Are we satisfied with the current operating points?
  - Next experiments: fuel-tracer PLIF; bowl geometry effects on mixture formation; establish operating points to focus on

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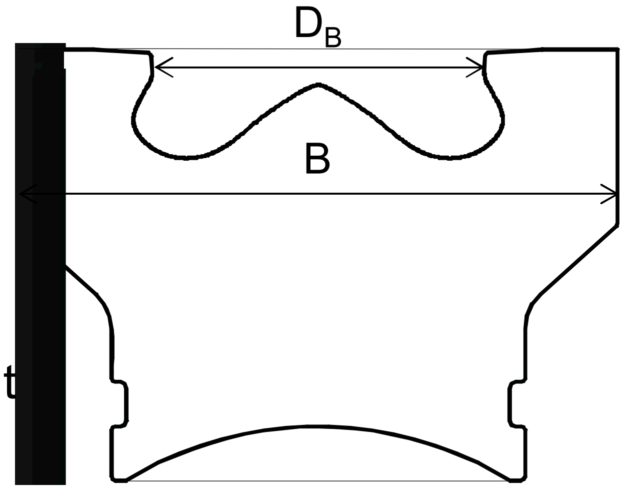
Background

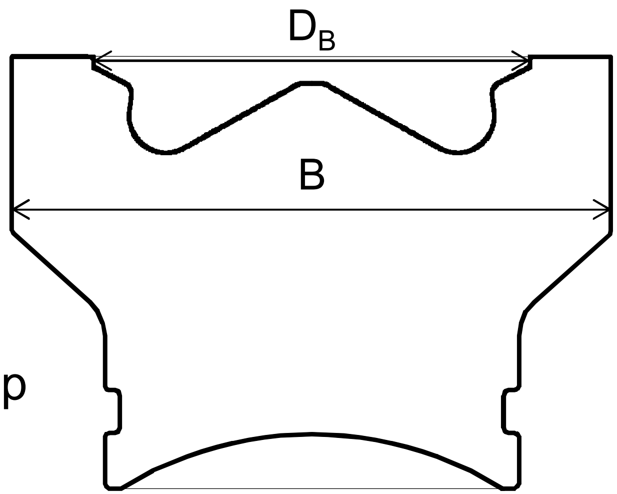
- Two piston bowl geometries with the same bowl volume available for in-cylinder flow asymmetry comparison.

Re-entrant



- Squish height (TDC) = 0.71 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

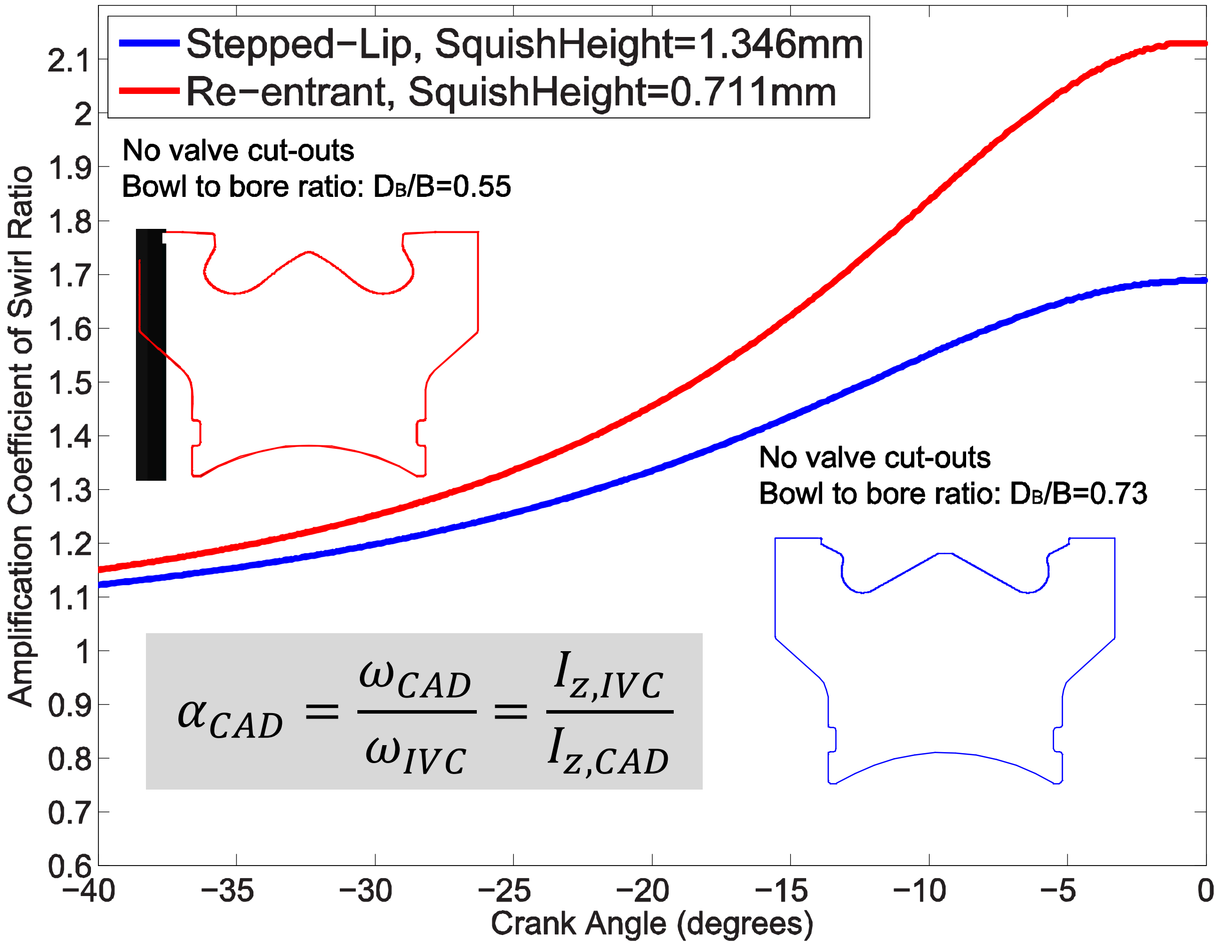
Stepped-lip



- Squish height (TDC) = 1.35 mm
- Compression ratio = 15.8
- Different optical distortion pattern
- No valve cut-outs
- Bowl to bore ratio: $D_B/B=0.73$

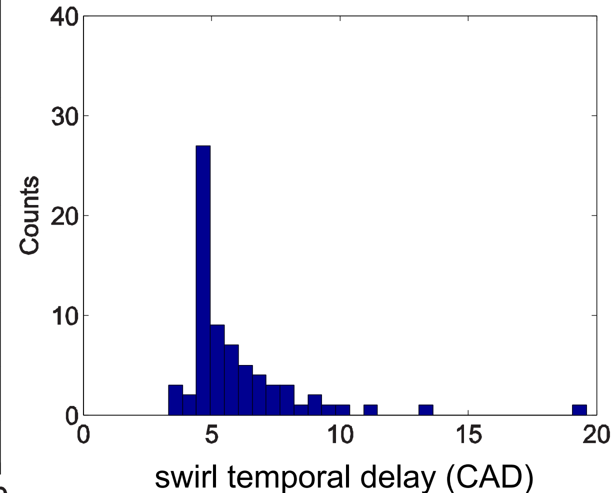
1-D theoretical analyses: swirl develops slower with stepped-lip piston geometry

- 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.



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

- This configuration mimics the current experimental setups.

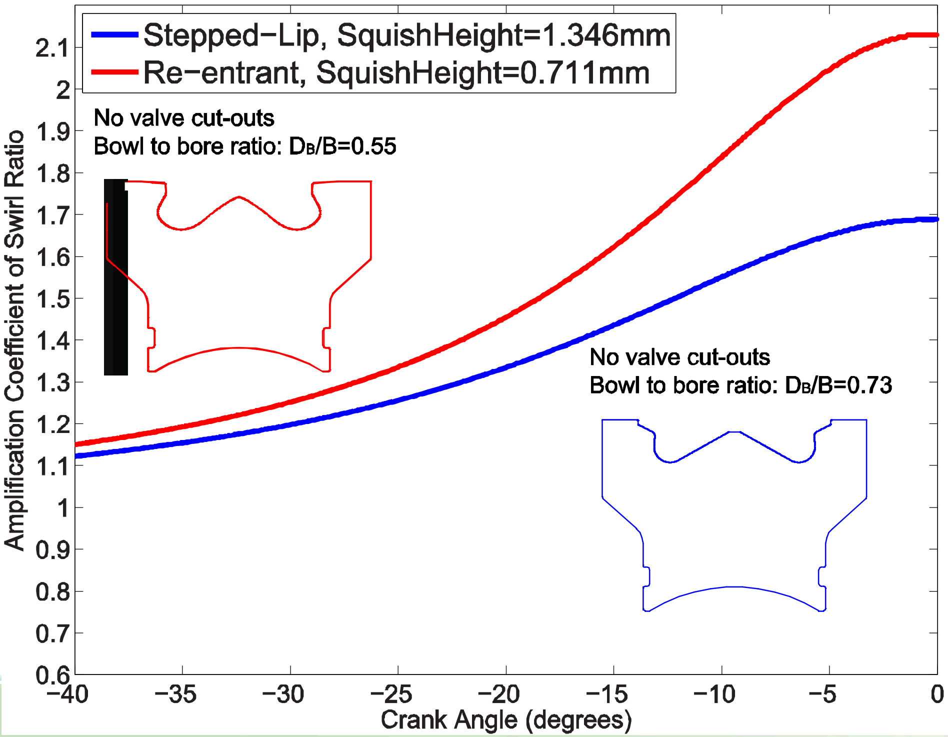


Swirl temporal delay measured from PIV confirms the result from 1-D theoretical analysis

- 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.

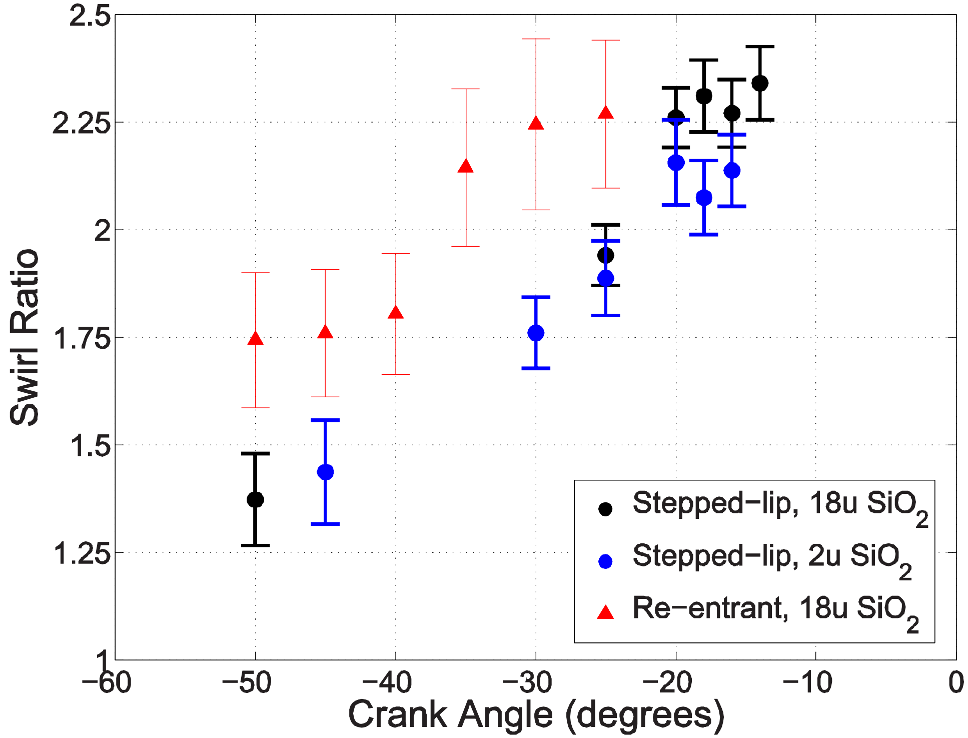
1-D Simulation

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



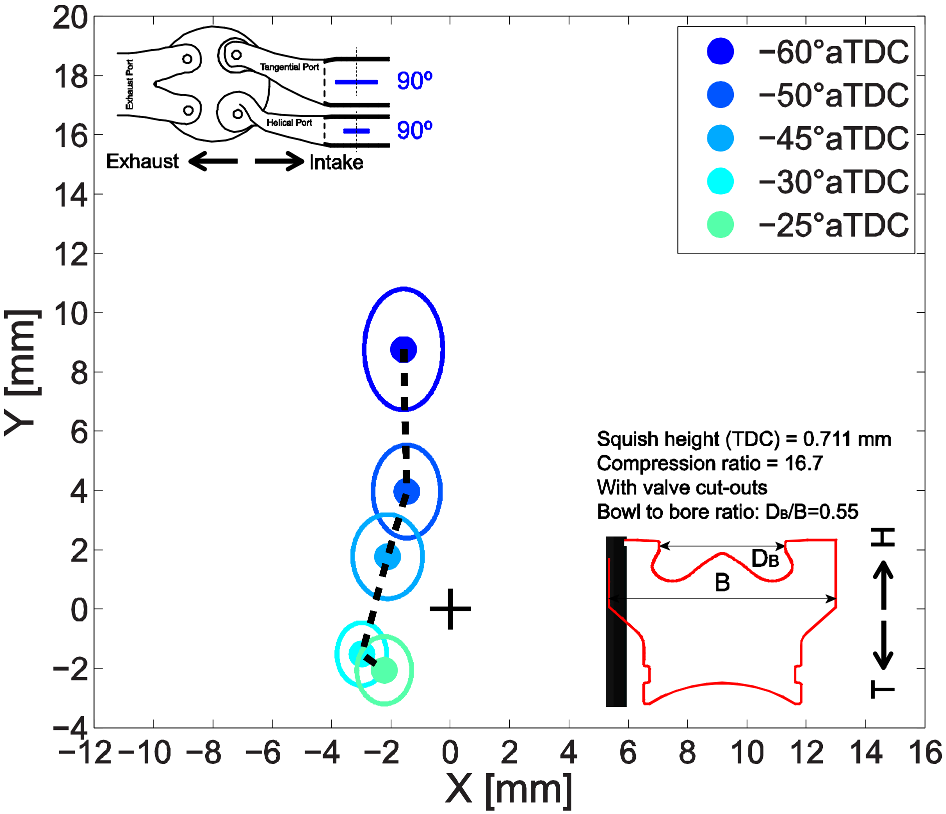
Experimental Results from PIV

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

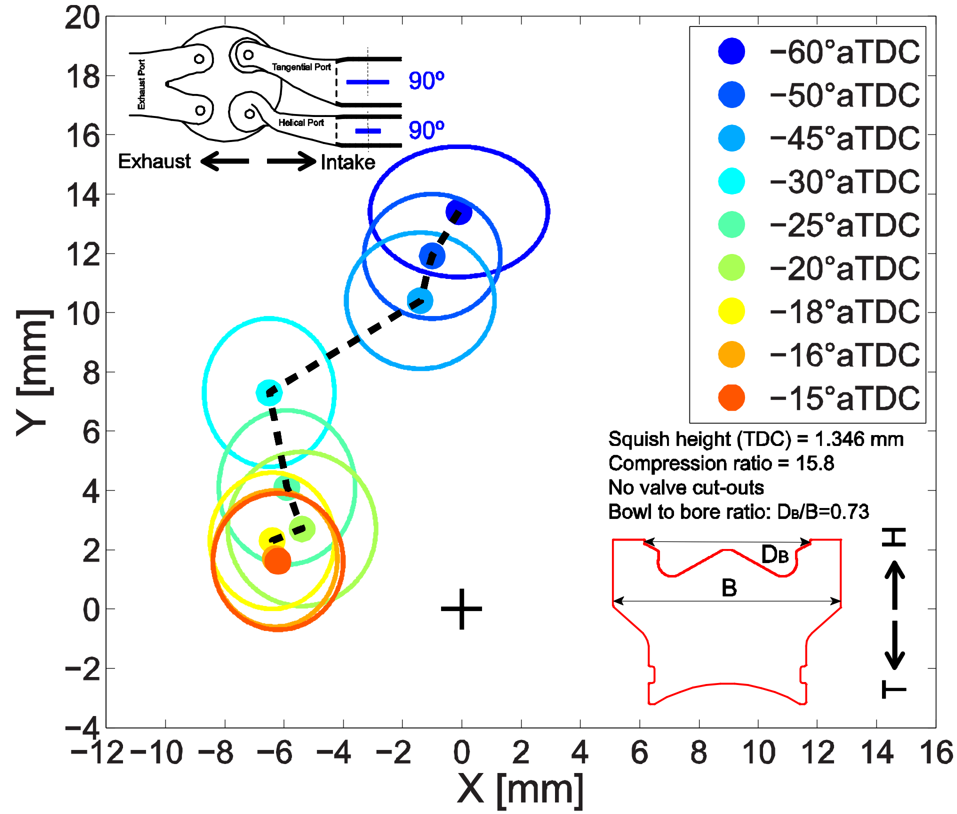


Late compression stroke: in-cylinder swirl is more eccentric … and … cyclic variability of swirl center location is greater with the stepped-lip piston (+increased squish height).

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.

Recap: piston geometry effects on swirl ratio

- Experiments were performed with different squish heights and with only one piston with valve cutouts
- Theory predicts delayed and less intense swirl ratio ramp-up during the compression stroke
  - Measurements agree qualitatively with this statement
- Swirl centering is less pronounced with the stepped-lip, and cyclic variability is greater, but the squish heights were different
- Current plan: get support from CFD results (may be possible before end of 2015)

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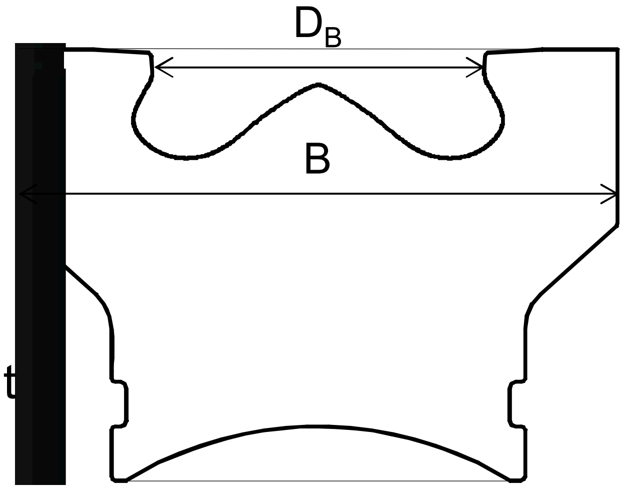
Pistons for comparison

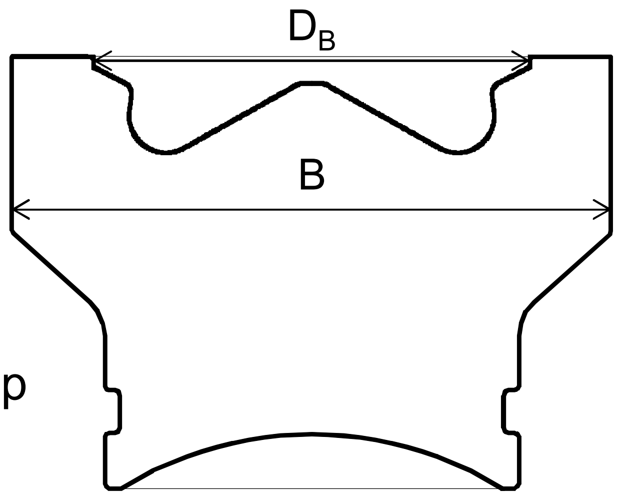
- Two piston bowl geometries with <u>the same bowl volume</u> (25.04 cc) available for baseline tests.

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.

Operating conditions

LTC (single injection)

Engine speed	1500 rpm
Intake charge mole fractions	O_2: 10% CO_2: 9% N_2: 81%
Intake temperature	99 °C
Intake pressure	~ 1.5 bar
$IMEP_g$	3.0 bar
Injected fuel	~ 11 mg/str
Injection pressure	860 bar
Global equivalence ratio	TBD
SSE	-42 ~ -12 CAD ATDC
SOI	TBD
Injection duration	~4.2 CAD
Swirl ratio (Ricardo)	2.2
TDC density	20.9
TDC temperature	909

Conventional (single/double injection)

Engine speed	1500 rpm
Intake charge mole fractions	O_2: 19.7% CO_2: 1.1% N_2: 79.2%
Intake temperature	80 °C
Intake pressure	~ 1.5 bar
$IMEP_g$	9.0 bar
Injected fuel (P/M)	1.4 / ~ 25 mg/str
Injection pressure	800 bar
Global equivalence ratio	TBD
SSE (pilot)	-19 ~ 2 CAD ATDC
Energizing dwell	1200 μs
Main inj. duration	~6.5 CAD
Swirl ratio (Ricardo)	2.2
TDC density	21.8
TDC temperature	925

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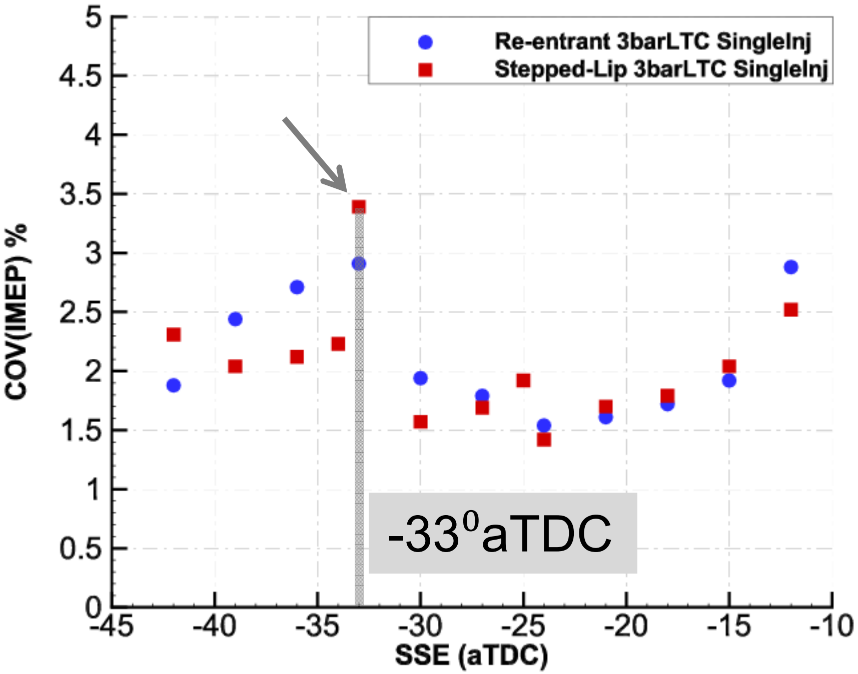
LTC case: COV(IMEP%) Evaluation

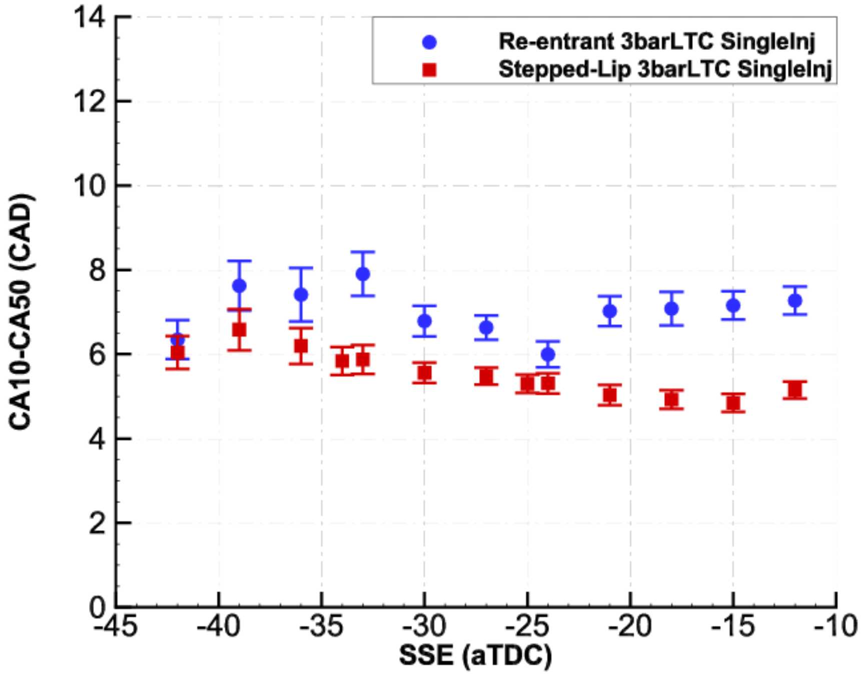
- Operating point:
  - 1500 rpm
  - 3 bar IMEPg (within ±3%)
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -42^{o}aTDC and -12^{o}aTDC.
- Stepped-lip piston exhibits a significant increase in COV(IMEP) at -33^{o}aTDC. <u>The trend around this point needs further confirmation.</u>



Start of main energizing

LTC case: Combustion Duration Evaluation

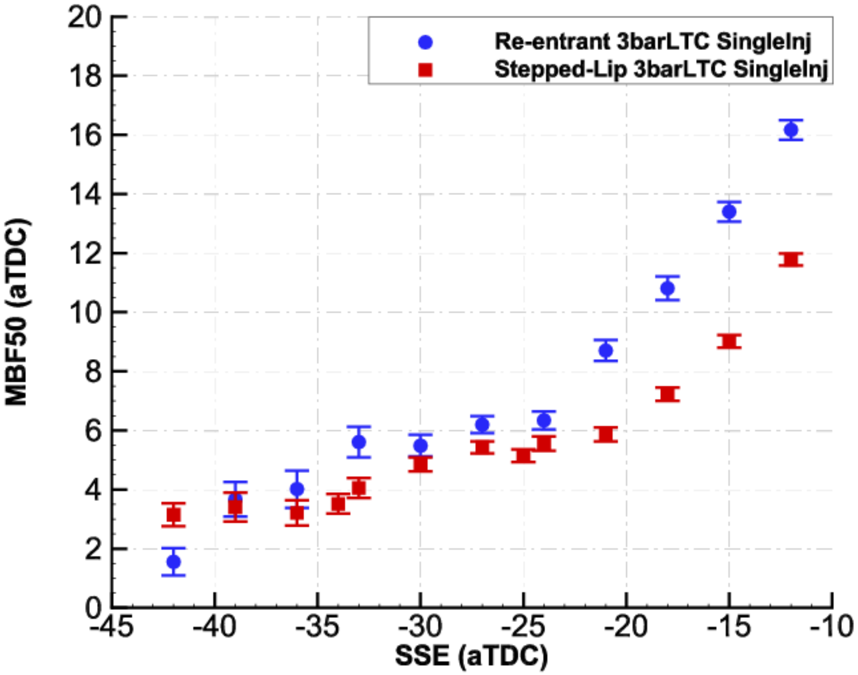
- Operating point:
  - 1500 rpm
  - 3 bar IMEPg
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -42°aTDC and -12°aTDC.
- Stepped-lip piston exhibits shorter CA10-CA50 durations



Start of main energizing

LTC case: Combustion Duration Evaluation

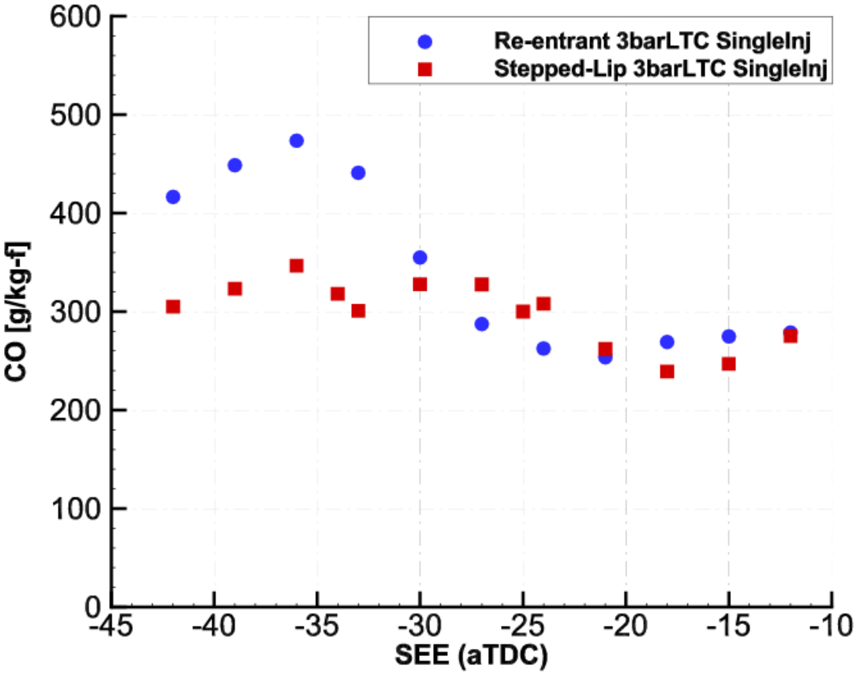
- Operating point:
  - 1500 rpm
  - 3 bar IMEPg
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -42°aTDC and -12°aTDC.
- CA50 usually occurs earlier with the stepped-lip piston for a given injection timing.



Start of main energizing

LTC case: CO Test

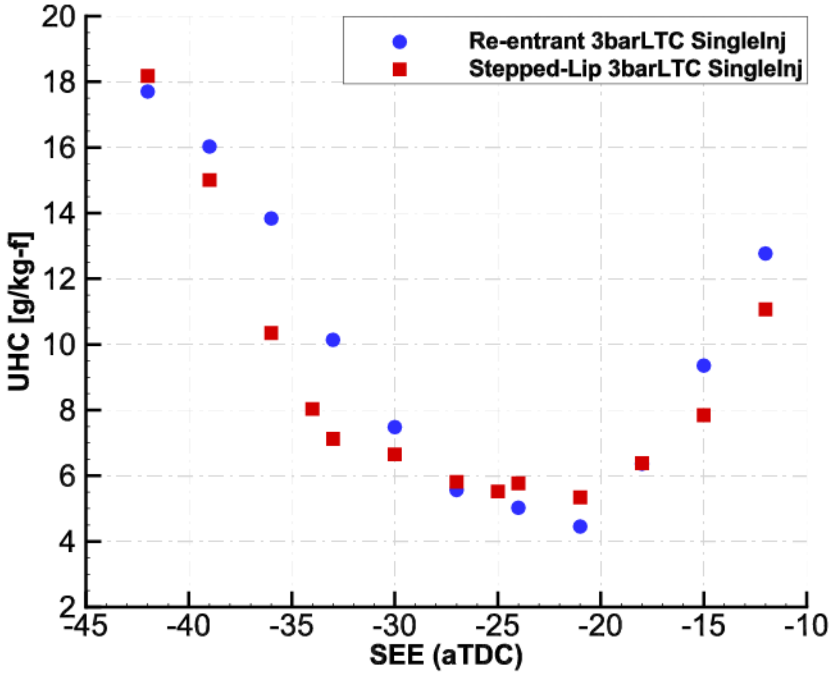
- Operating point:
  - 1500 rpm
  - 3 bar IMEPg
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -42°aTDC and -12°aTDC.
- Stepped-lip piston exhibits significant decrease in CO (up to 27%) for injection prior to -30°aTDC.



Start of main energizing

LTC case: UHC Test

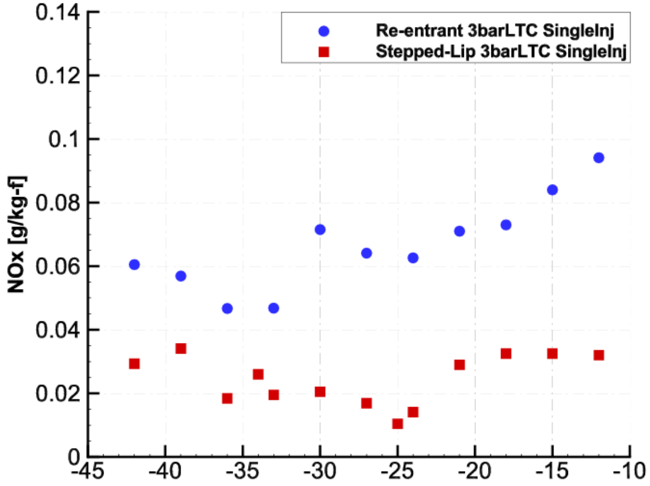
- Operating point:
  - 1500 rpm
  - 3 bar IMEPg
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -42°aTDC and -12°aTDC.
- Stepped-lip piston exhibits slight decrease in UHC at injection between -39°aTDC and -30°aTDC.
- UHC trends are plausible.

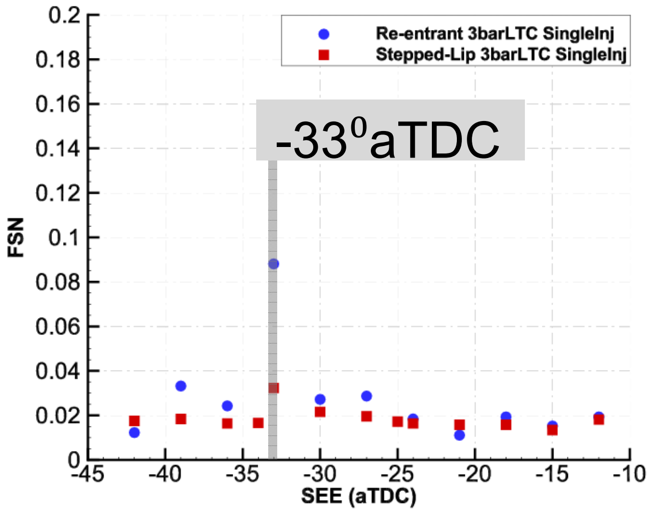


Start of main energizing

LTC case: NOx and soot

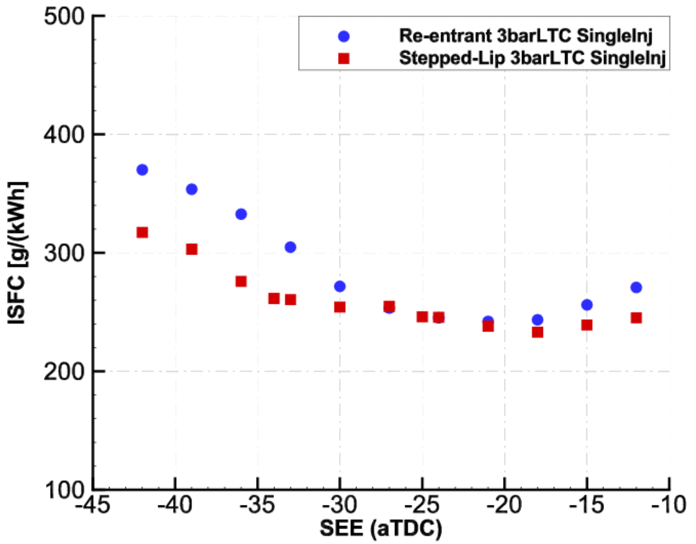
- Operating point:
  - 1500 rpm
  - 3 bar IMEPg
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -42°aTDC and -12°aTDC.
- NOx and soot emissions are low for LTC conditions.
- Stepped-lip piston exhibits slight decrease in NOx.
- Piston geometry impact on FSN is not significant except at -33°aTDC.

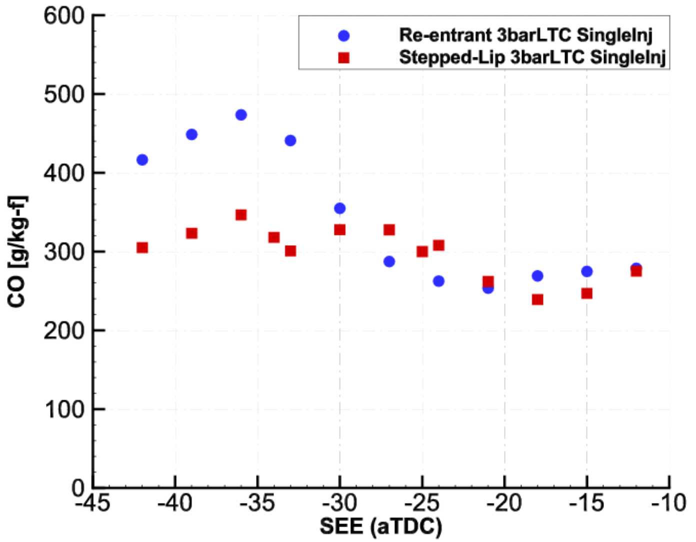




LTC case: ISFC Evaluation

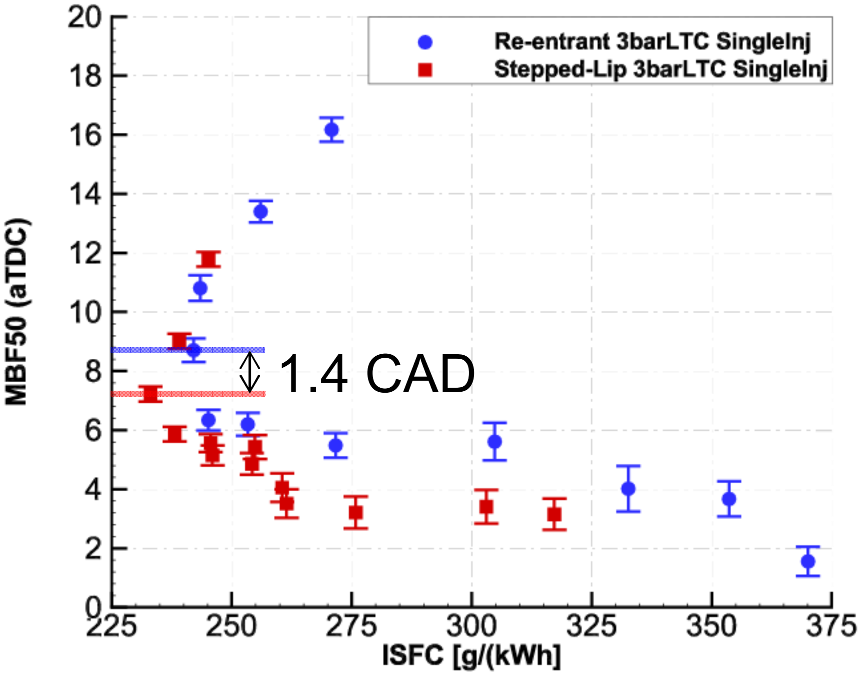
- Operating point:
  - 1500 rpm
  - 3 bar IMEPg
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -42°aTDC and -12°aTDC.
- Stepped-lip piston exhibits ~15% decrease in ISFC at injection between -42°aTDC and -30°aTDC. It is consistent with lower CO emissions.





Combustion Phasing Evaluation

- Operating point:
  - 1500 rpm
  - 3 bar IMEPg
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -42°aTDC and -12°aTDC.
- The optimum combustion phasing for minimum ISFC is slightly earlier (1.4 CAD) for the stepped-lip piston



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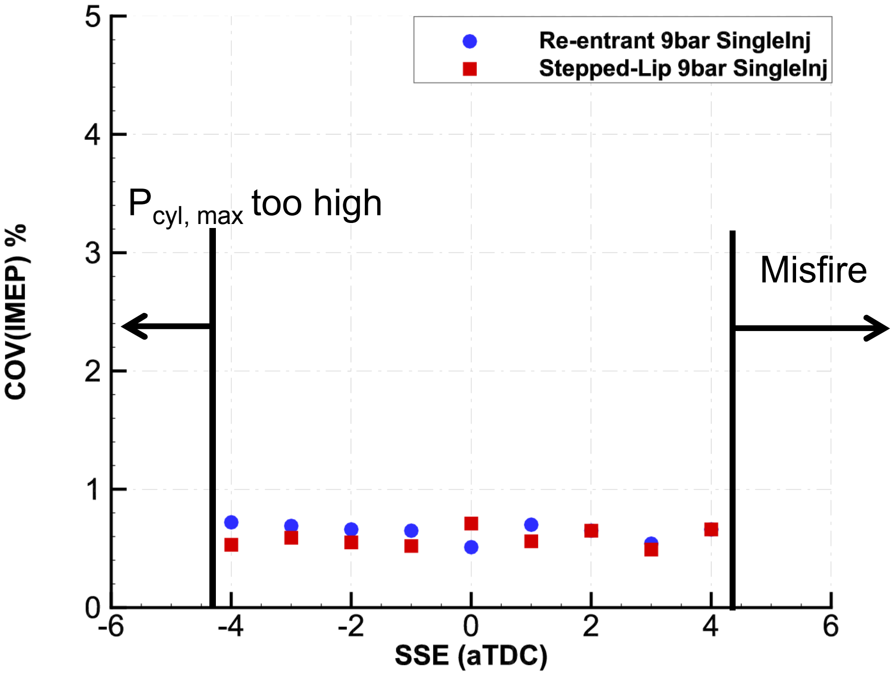
Conventional case: COV(IMEP%) Evaluation

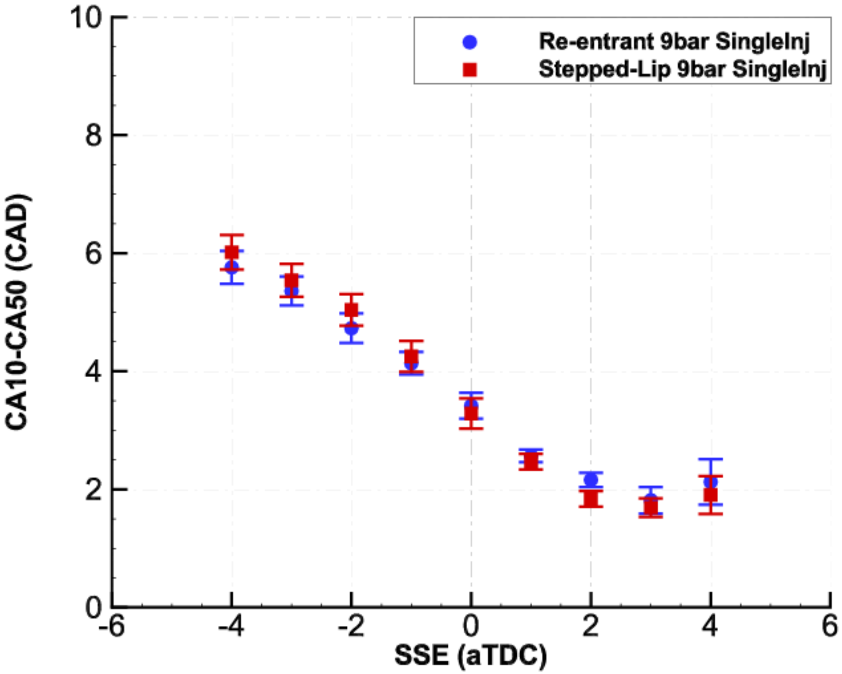
- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -4°aTDC and 4°aTDC.
- Piston geometry effect is not significant.



Start of main energizing

Combustion Duration Evaluation

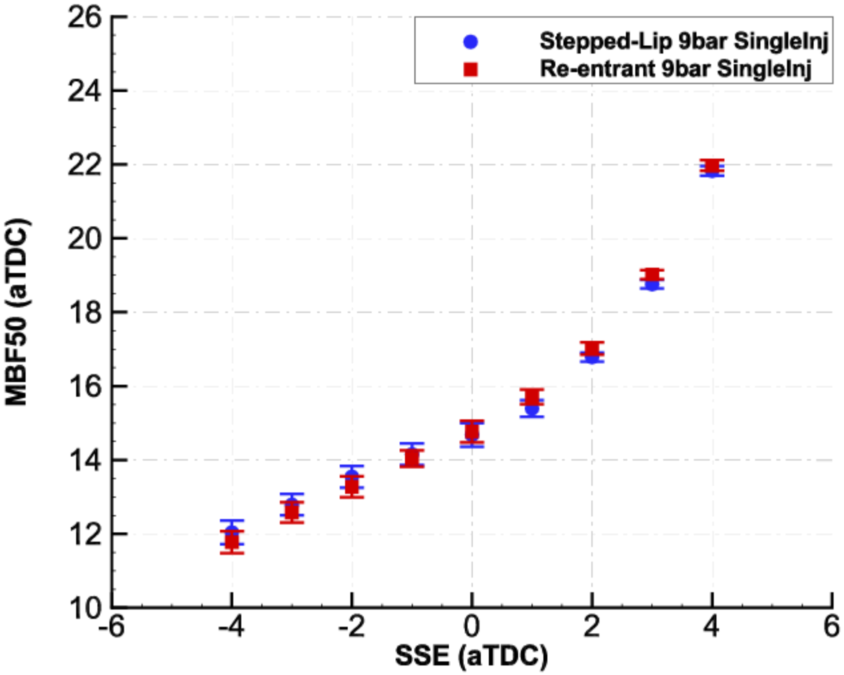
- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -4°aTDC and 4°aTDC.
- Piston geometry effect is not significant.



Start of main energizing

Combustion Phasing Evaluation

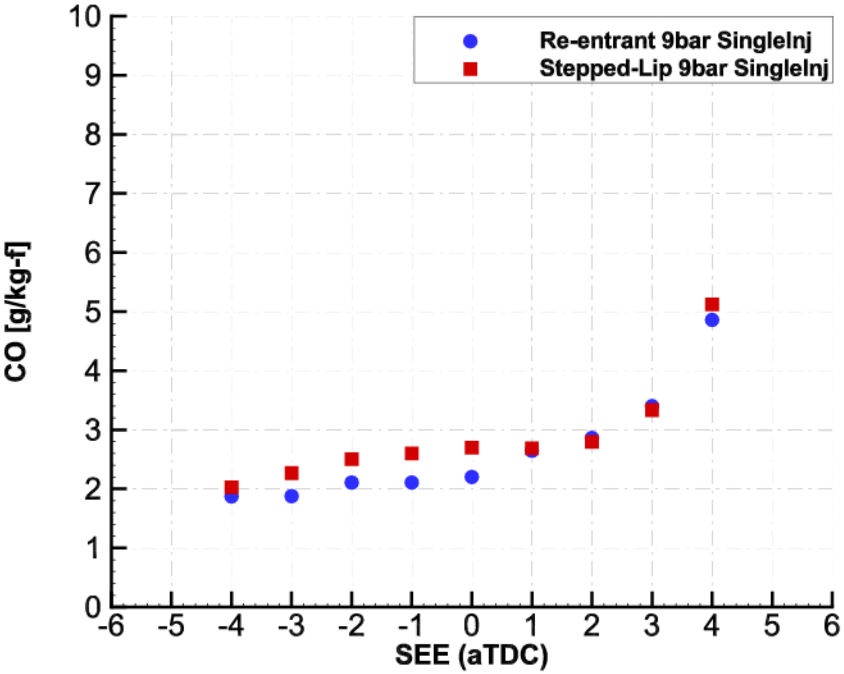
- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -4°aTDC and 4°aTDC.
- Combustion phasing retards with injection timing.
- Piston geometry effect is not significant.



Start of main energizing

Conventional case: CO Test

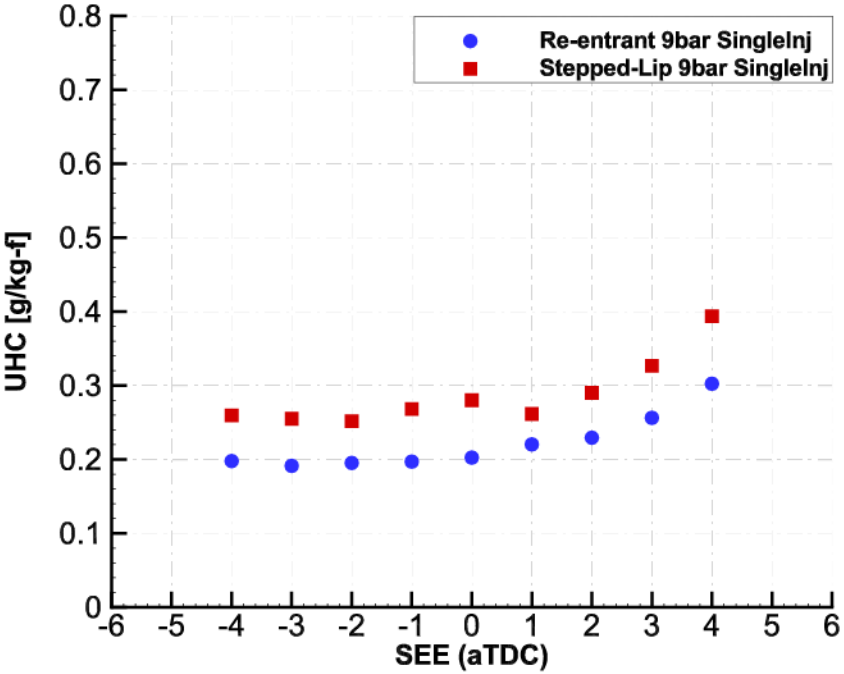
- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -4°aTDC and 4°aTDC.
- Stepped-lip piston exhibits slight increase in CO (up to 11%) at injection between -3°aTDC and TDC.



Start of main energizing

Conventional case: UHC Test

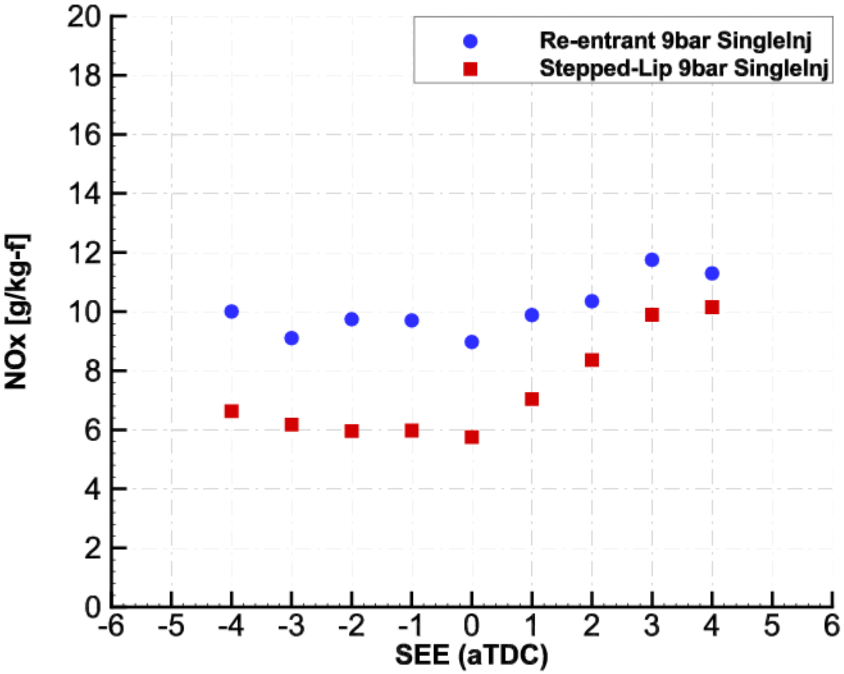
- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -4°aTDC and 4°aTDC.
- Low UHC emissions.
- Stepped-lip piston exhibits slight increase in UHC (up to 38%).



Start of main energizing

Conventional case: NOx Test

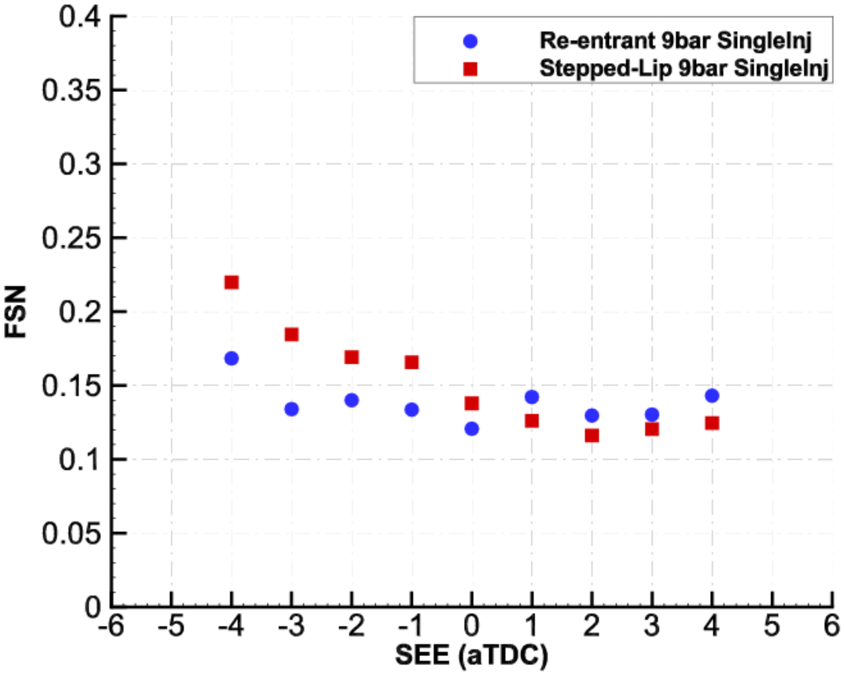
- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -4^{o}aTDC and 4^{o}aTDC.
- Stepped-lip piston exhibits a decrease in NOx (up to 35%).



Start of main energizing

Conventional case: Soot Test

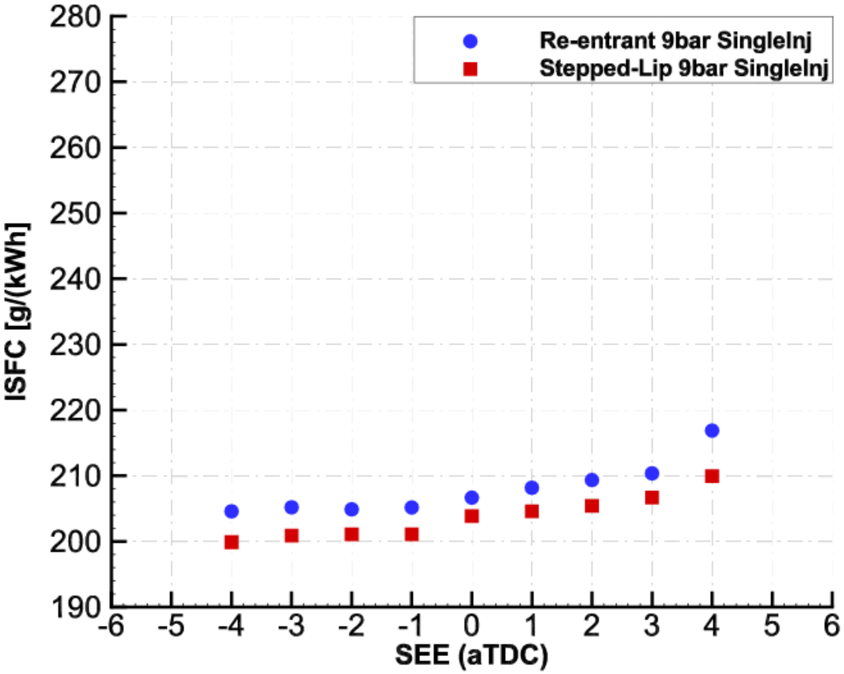
- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -4°aTDC and 4°aTDC.
- Stepped-lip piston exhibits an increase in soot (up to 31%) at injection prior to TDC.



Start of main energizing

Conventional case: ISFC Evaluation

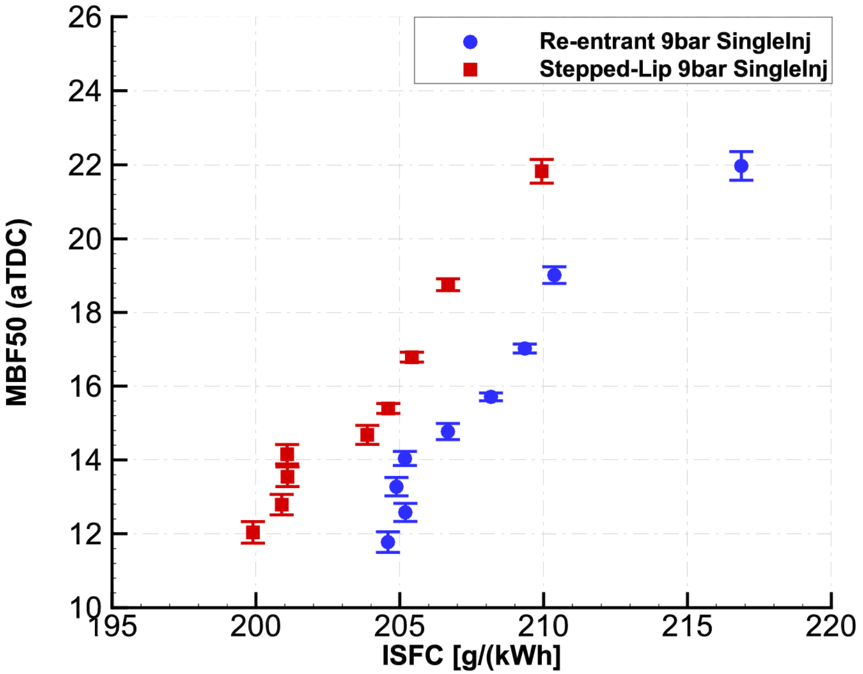
- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -4°aTDC and 4°aTDC.
- Stepped-lip piston exhibits improved ISFC (up to 3%).



Start of main energizing

Combustion Phasing Evaluation

- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Single injection
- Constant P_{rail}, IMEPg.
- Injection sweep between -4°aTDC and 4°aTDC.
- The optimum combustion phasing to reach minimum ISFC is 12°aTDC for both piston geometries.



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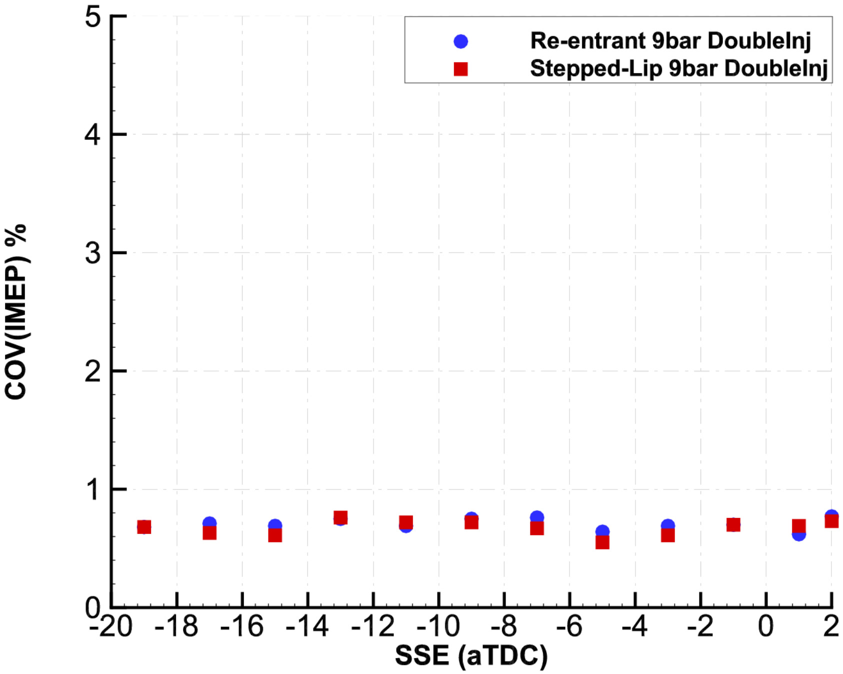
Conventional case: COV(IMEP%) Evaluation

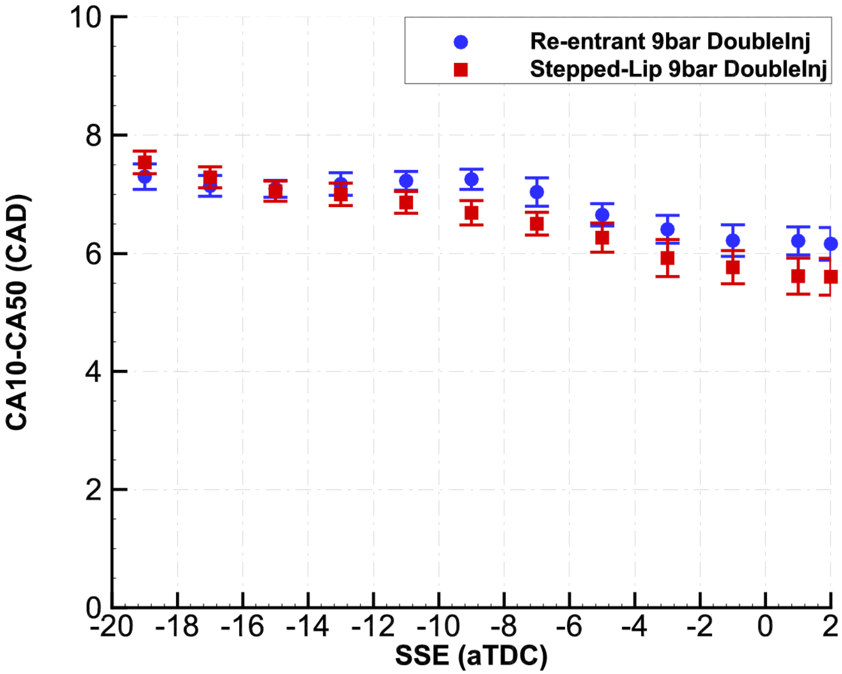
- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Pilot-main injection (fixed dwell at 1200μs)
- Constant P_{rail}, IMEPg.
- Pilot-main injection induces wider operating range at part load.
- Injection sweep between -19^{o}aTDC and 2^{o}aTDC.
- Piston geometry effect is not significant.



Start of pilot energizing

Combustion Duration Evaluation

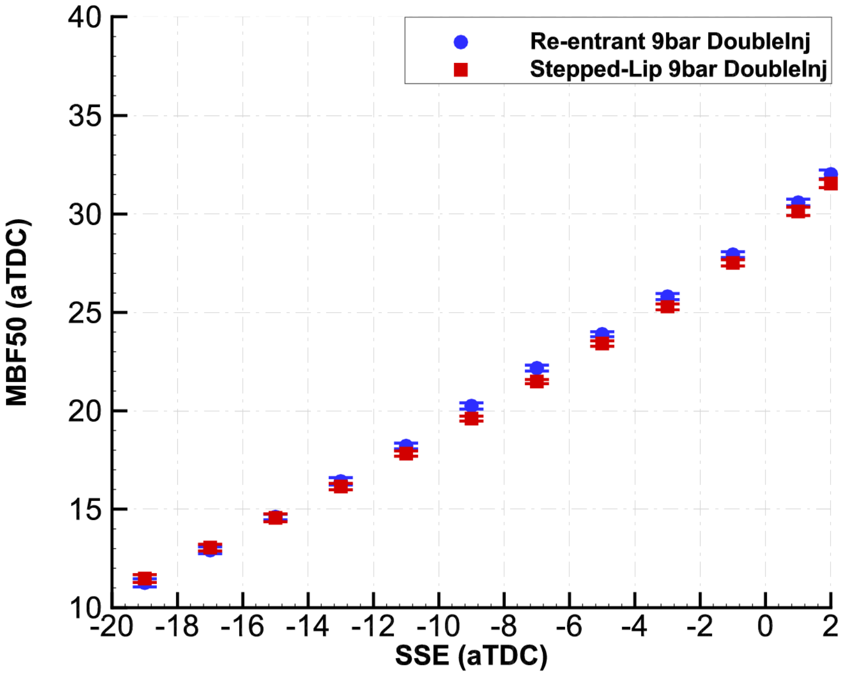
- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Pilot-main injection (fixed dwell at 1200µs)
- Constant P_{rail}, IMEPg.
- Injection sweep between -19^{o}aTDC and 2^{o}aTDC.
- Stepped-lip piston exhibits slight shorter combustion duration.



Start of pilot energizing

Combustion Phasing Evaluation

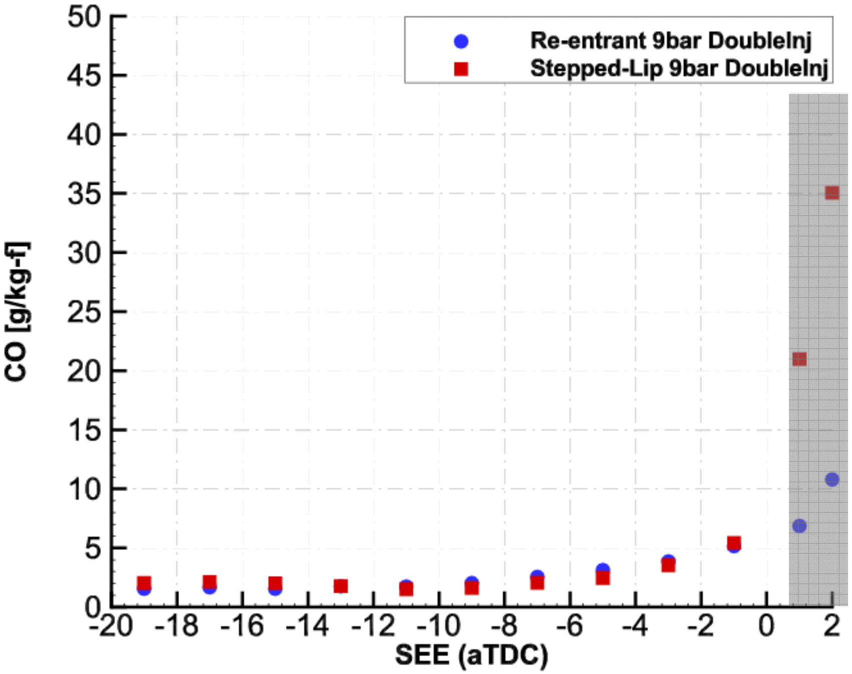
- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Pilot-main injection (fixed dwell at 1200μs)
- Constant P_{rail}, IMEPg.
- Injection sweep between -19°aTDC and 2°aTDC.
- Combustion phasing retards with injection timing.
- Piston geometry effect is not significant.



Start of pilot energizing

Conventional case: CO Test

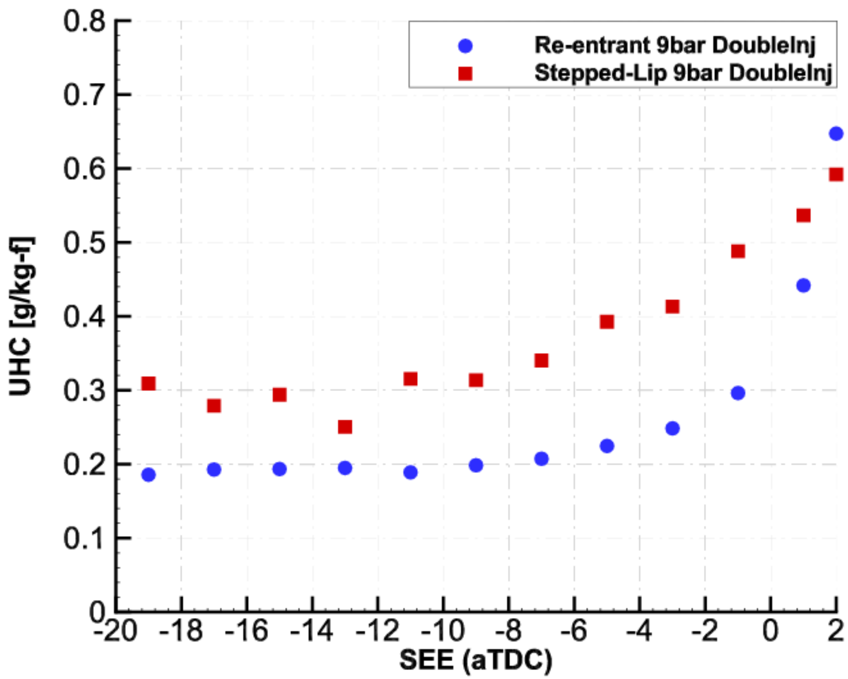
- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Pilot-main injection (fixed dwell at 1200μs)
- Constant P_{rail}, IMEPg.
- Injection sweep between -19^{o}aTDC and 2^{o}aTDC.
- Stepped-lip piston exhibits rapid increase in CO at pilot injection after TDC.



Start of pilot energizing

Conventional case: UHC Test

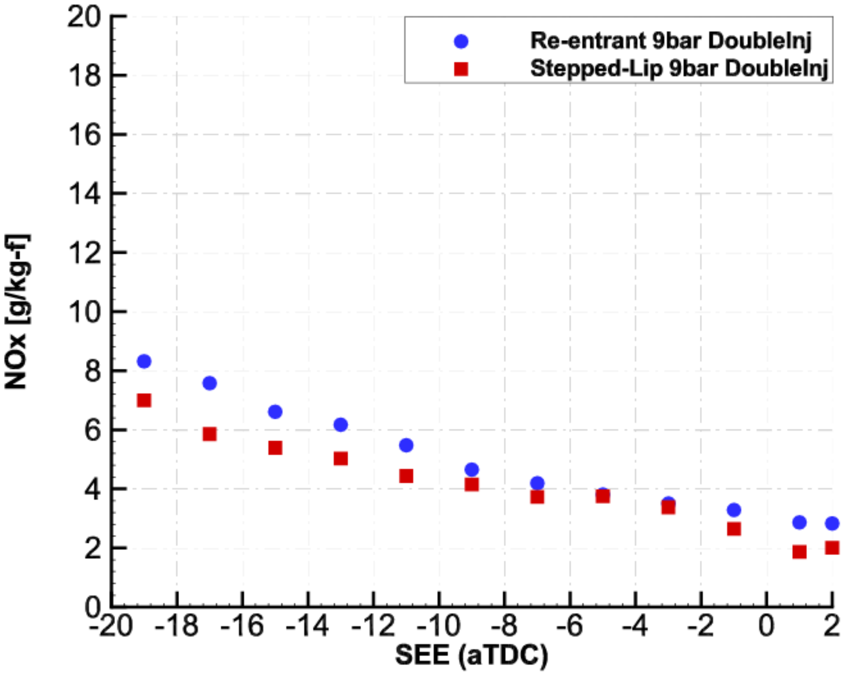
- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Pilot-main injection (fixed dwell at 1200μs)
- Constant P_{rail}, IMEPg.
- Injection sweep between -19^{o}aTDC and 2^{o}aTDC.
- Low UHC emission.
- Stepped-lip piston exhibits slight increase in UHC (up to 50%) prior to TDC.



Start of pilot energizing

Conventional case: NOx Test

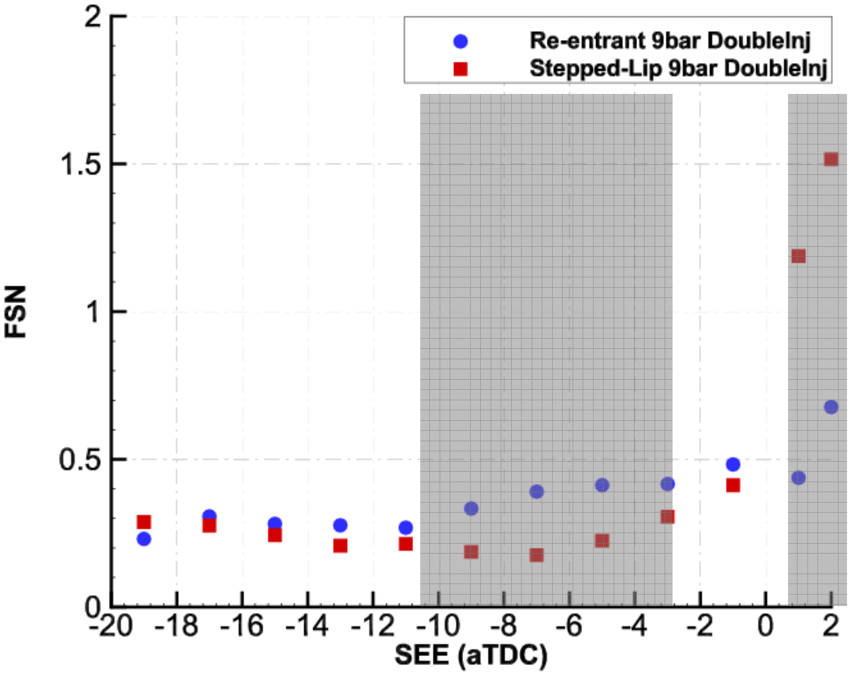
- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Pilot-main injection (fixed dwell at 1200μs)
- Constant P_{rail}, IMEPg.
- Injection sweep between -19°aTDC and 2°aTDC.
- NOx decreases with retarding pilot injection.
- Stepped-lip piston exhibits slight decrease in NOx (up to 15%).



Start of pilot energizing

Conventional case: Soot Test

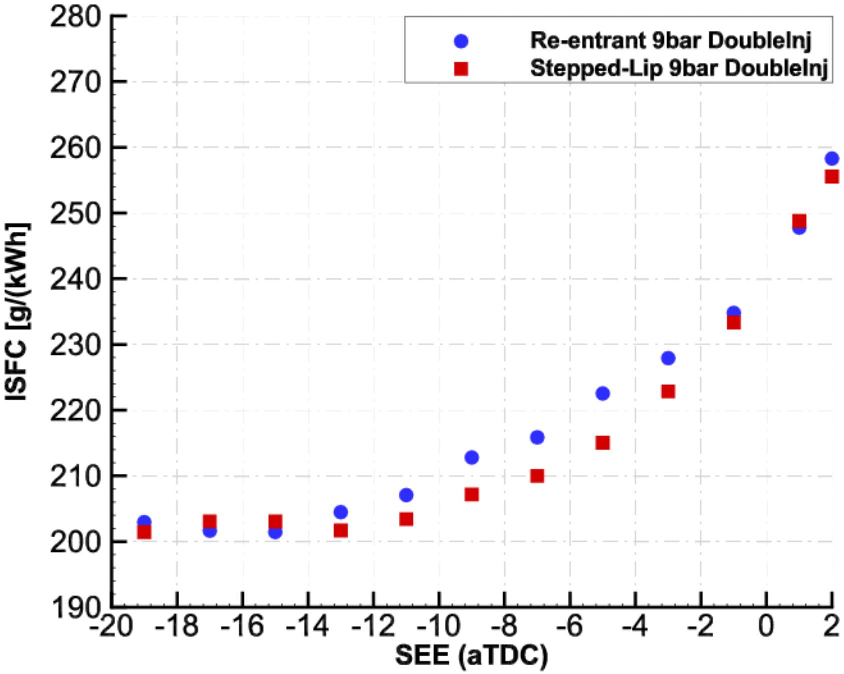
- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Pilot-main injection (fixed dwell at 1200μs)
- Constant P_{rail}, IMEPg.
- Injection sweep between -19°aTDC and 2°aTDC.
- Stepped-lip piston exhibits rapid increase in soot after TDC, while it yields in 55% of decrease in soot around -7°aTDC.



Start of pilot energizing

Conventional case: ISFC Evaluation

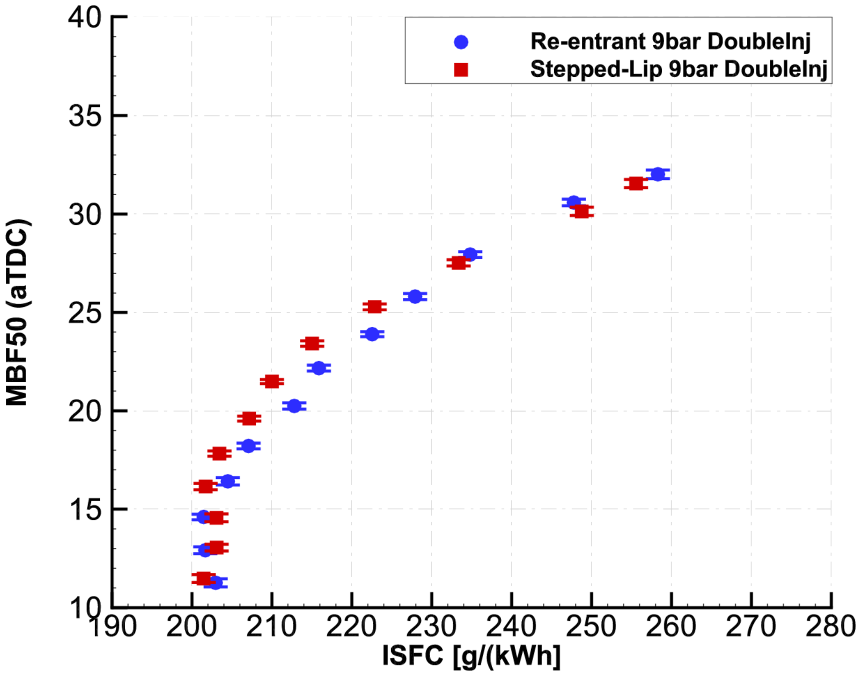
- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Pilot-main injection (fixed dwell at 1200µs)
- Constant P_{rail}, IMEPg.
- Injection sweep between -19^{o}aTDC and 2^{o}aTDC.
- ISFC increases with stepped-lip piston exhibits slight decrease in ISFC (up to 5%).



Start of pilot energizing

Combustion Phasing Evaluation

- Operating point:
  - 1500 rpm
  - 9 bar IMEPg
  - Pilot-main injection (fixed dwell at 1200μs)
- Constant P_{rail}, IMEPg.
- Injection sweep between -19°aTDC and 2°aTDC.
- The optimum combustion phasing to reach minimum ISFC is 12°aTDC for both piston geometries.



Summary: metal piston testing

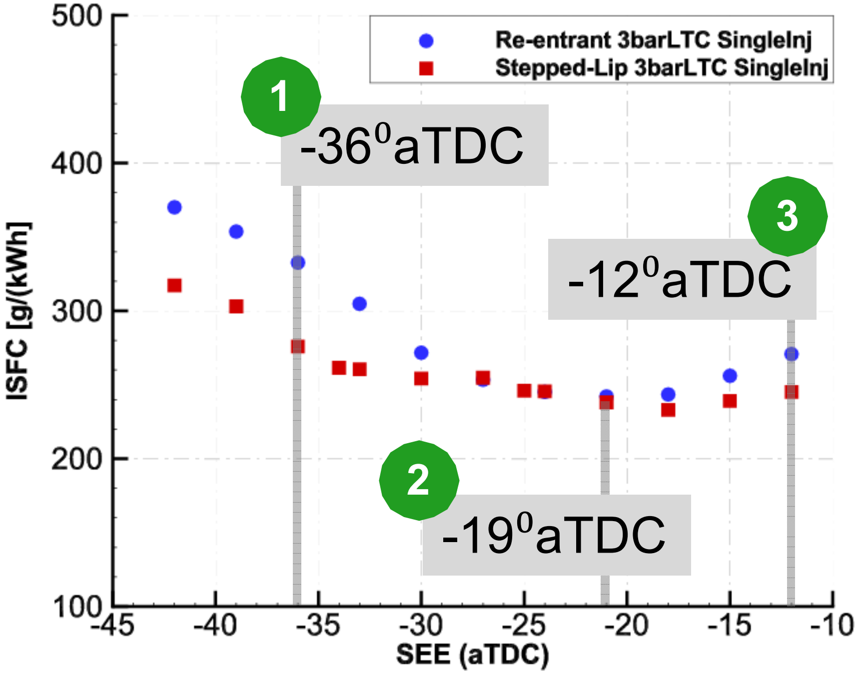
- Metal piston testing results: injection timing sweeps; stepped lip vs. conventional re-entrant bowl; emissions, efficiency data
  - LTC, light load (3bar)
    - Stepped-lip piston exhibits significant decrease in CO (up to 27%) with early injection.
    - Stepped-lip piston exhibits slight decrease in UHC at injection between -39^{o}aTDC to -30^{o}aTDC.
    - Stepped-lip piston exhibits ~15% decrease in ISFC with early injection.
    - COV(IMEP)% is sensitive to injection timing with stepped-lip geometry? (needs further confirmation)
  - Conventional, part load (9bar), single injection
    - Stepped-lip piston exhibits a decrease in NOx (up to 35%).
    - Stepped-lip piston exhibits slight decrease in ISFC (up to 3%).
  - Conventional, part load (9bar), pilot-main injection (to widen the sweep range)
    - Stepped-lip piston exhibits rapid increase in CO&soot with pilot injection after TDC, while it yields in 55% of decrease in soot with pilot injection around -7^{o}aTDC.
    - Stepped-lip piston exhibits slight decrease in ISFC (up to 5%) and NOx (up to 15%).

Progress Report Outline

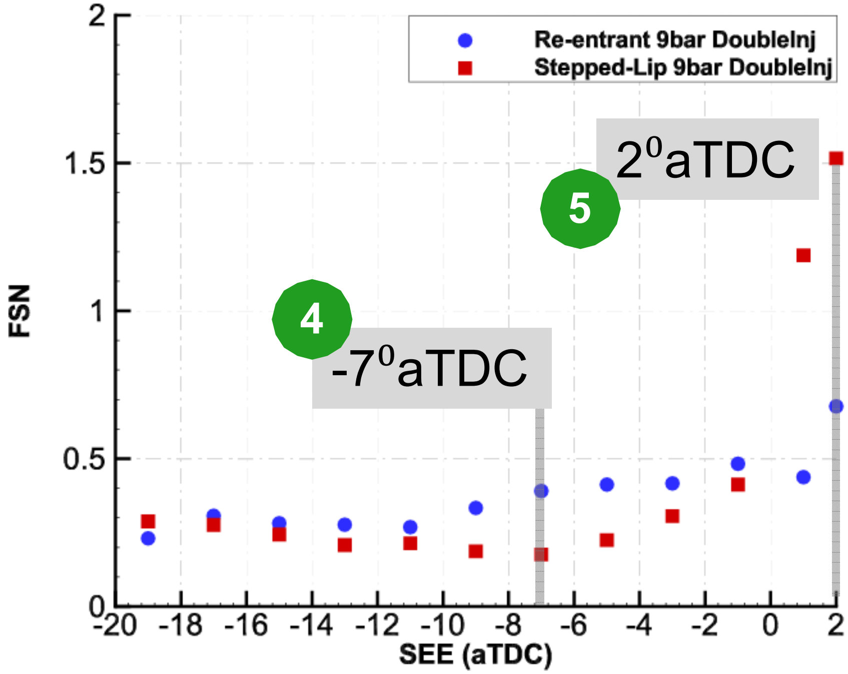
- Review: current state of knowledge of bowl geometry effects on motored flow from PIV experiments and 1-D theoretical analyses
- Metal piston testing results: injection timing sweeps; stepped lip vs. conventional re-entrant bowl; emissions, efficiency data
  - LTC, light load (3bar)
  - Conventional, part load (9bar), single injection
  - Conventional, part load (9bar), pilot-main injection
- Where do we go from here?
  - Are we satisfied with the current operating points?
  - Next experiments: fuel-tracer PLIF; bowl geometry effects on mixture formation; establish operating points to focus on

Points of interest for optical investigation…

LTC, light load (3bar), single injection



Conventional, part load (9bar), pilot-main injection



1. Stepped-lip geometry provides benefits in CO, UHC and ISFC – why / how?
2. Why is operation so similar despite differences in mixture formation?
3. What changes at later injection timings?

4, 5. How/why does piston geometry affect the soot-NOx trade-off for intermediate and late injection timings?

Thank you for your attention!

Fuel Injector

- Bosch CRI 2.2
  - 7 evenly spaced holes
  - Outlet diameter: 139 µm
  - ks: 1.5 / 86
  - 149° included angle
  - Flow rate: 440 cm^3/30s @100 bar