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Analysis of Efficiency Improvements in a Light-Duty Diesel Engine with a Stepped-Lip Piston

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Abstract

As reported in the literature, several factors are reported to contribute to improved efficiency and emissions with the use of stepped-lip piston bowls in swirl-supported, DI diesel engines: reduced wall heat loss; increased late-cycle heat release rates; and improved air utilization. However, the physical mechanisms responsible for many of these improvements are not well understood, or are not well documented. In this work, performance testing is carried out with a conventional, re-entrant piston and with a stepped-lip piston for both conventional diesel and dilute, premixed operation. First-law thermodynamic analyses suggest that differences in wall heat loss between the two piston bowl shapes cannot be resolved during the closed portion of the cycle. For conventional diesel operation, thermal efficiency improvements are most closely related to a higher degree of constant volume combustion with the stepped-lip piston. For dilute, largely premixed operation, differences in combustion efficiency lead to improved fuel conversion efficiency for some operating points with the stepped-lip piston. Ongoing and future studies, both experimental and computational, will be devoted to building an understanding of mixture formation and late-cycle turbulent mixing processes for both piston geometries.

Outline

Introduction and motivation

- Efficiency and emissions advantages of stepped-lip piston designs

Thermodynamic analysis: conventional vs. stepped-lip piston bowl

- Conventional combustion
- Low-temperature combustion

Conclusions:

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

Ricardo’s Twin Vortex combustion chamber design

- Engineering target: eliminate or reduce exhaust aftertreatment requirements for off-road applications
- Key design parameters:
  - Piston bowl shape
  - Spray cone angle
  - In-cylinder swirl
- Dual counter-rotating toroidal vortices act to enhance fuel-air mixing, thus reducing particulate emissions[1]
- JCB Ecomax T4: “off-highway industry’s cleanest” engine[2]

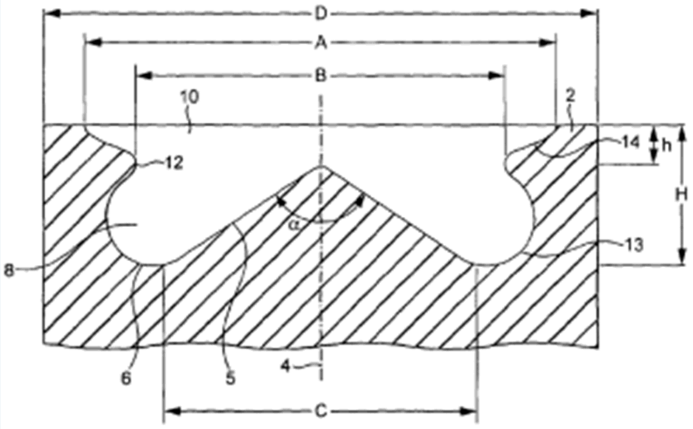


FIG. 1

From: Cornwell, R., F. Conicella, 2014. “Direct injection diesel engines”, US Patent 8,770,168 (Ricardo)

1: Crosse, J., “Going clean – off highway”, Ricardo Quarterly Review: Q2 2010, pp. 16-21, Ricardo plc, June 2010.
2: Smith, A., “Ricardo low emissions combustion technology helps JCB create the off-highway industry’s cleanest engine”, Ricardo Media Office Press Release, March 19,2010

Doosan's ultra-low particulate combustion (ULPC) piston

- Improve air utilization by dividing fuel spray into two combustion regions:
  - Deep in the bowl
  - In the near-squish region
- Slight changes in simulated vertical-plane late-cycle vortex structures, but their significance is unclear
- Leaner mixtures are formed over a larger region of the combustion chamber, which "provided the faster soot oxidation than the baseline"[1]

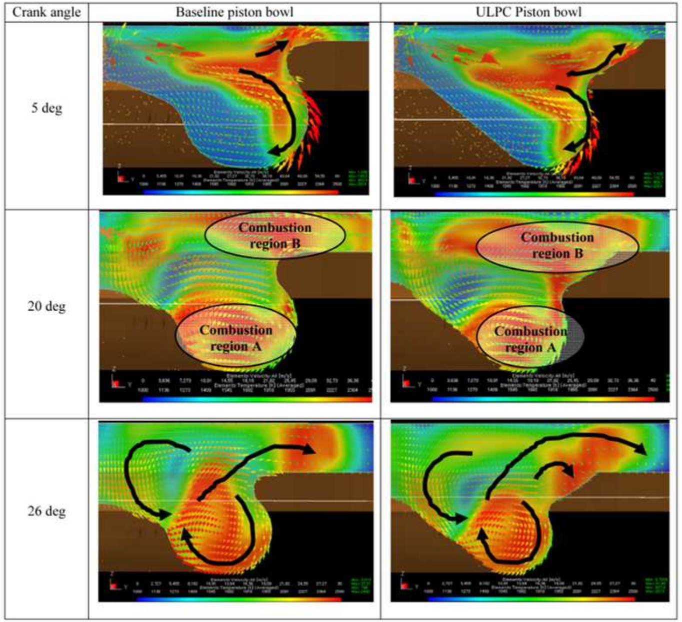


Figure 7. Comparison of flow pattern and contour plots of the temperature distribution in the baseline and ULPC piston

From [1]: Yoo, D., Kim, D., Jung, W., Kim, N. et al., "Optimization of Diesel Combustion System for Reducing PM to Meet Tier4-Final Emission Regulation without Diesel Particulate Filter," SAE Technical Paper 2013-01-2538, 2013, doi:10.4271/2013-01-2538.

Ford's 6.7L Power Stroke® Medium-Duty Engine

- Most significant elements of combustion system design[1]:
  - Bowl shape
  - Swirl ratio
  - Nozzle parameters
- With the stepped-lip bowl:
  - More even fuel-air mixture distribution[1]
  - Reduced late-cycle wall heat loss[1]
  - Improved efficiency[1,2]
  - Higher late-cycle heat release rates[2]
  - Reduced particulate emissions[2]
- Benefits diminish at high speeds/loads[2]

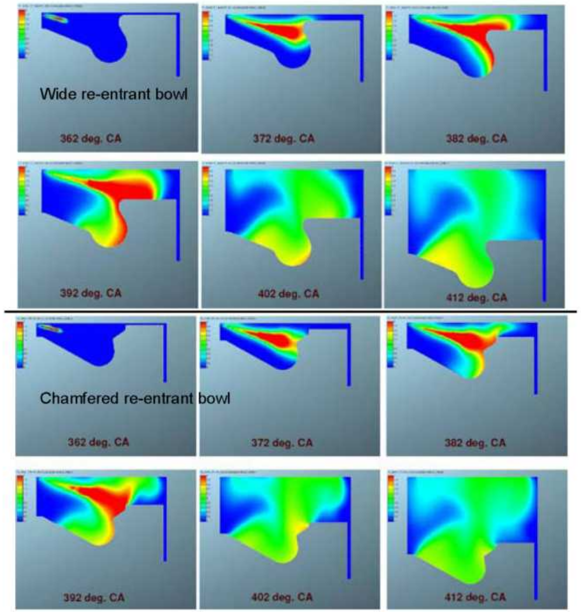


Figure 3. CFD provided equivalence ratio fields for the wide (top) and chamfered (bottom) re-entrant bowls early in the expansion stroke.

From 1: Styron, J., Baldwin, B., Fulton, B., Ives, D. et al., "Ford 2011 6.7L Power Stroke® Diesel Engine Combustion System Development," SAE Technical Paper 2011-01-0415, 2011, doi:10.4271/2011-01-0415.

2: 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.

Toyota's 2.8L ESTEC 1GD-FTV engine

- Impact of stepped-lip bowl on heat loss for a single operating point[1]:
  - Increased loss to cylinder head surface
  - Decreased loss to piston surface
  - Overall: slight decrease in wall heat loss (~10 J; 2400 rpm, 7 bar BMEP)

- In the squish region, more soot is formed initially, but it oxidizes faster
  - CFD simulations suggest that "…combustion conditions in the squish area become leaner" as combustion progresses[1]

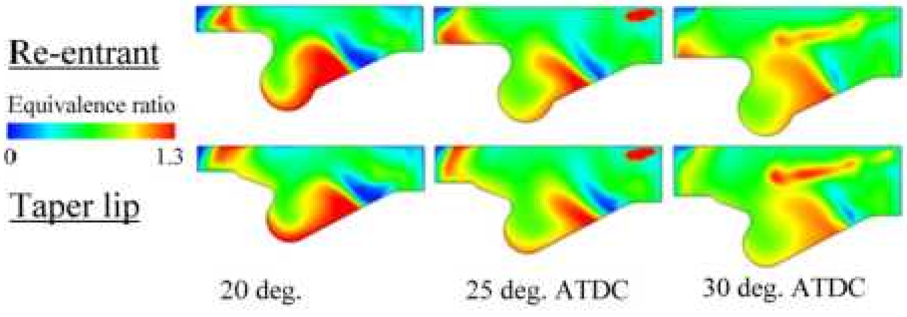


Figure 7. Distribution of in-cylinder equivalence ratio calculated by STAR-CD (2,400 rpm, 0.7 MPa).

From 1: Kogo, T., Hamamura, Y., Nakatani, K., Toda, T. et al., "High Efficiency Diesel Engine with Low Heat Loss Combustion Concept - Toyota's Inline 4-Cylinder 2.8-Liter ESTEC 1GD-FTV Engine -," SAE Technical Paper 2016-01-0658, 2016, doi:10.4271/2016-01-0658.

Daimler's OM654: stepped-lip bowl in a passenger car

- Considered by National Research Council to be an "advanced-level CI engine"[2]
  - Specific max torque density: 200 Nm/L[1]
- Advantages of the stepped-lip bowl[1]:
  - Very good air utilization; low particulate emissions
  - Faster burning rates; improved efficiency compared to omega-bowl
  - Changed flow behavior reduces cylinder wall heat loss; improves cylinder head surface temperature uniformity
  - "Fresh charge curtain" reduces wall-wetting and soot entering into oil

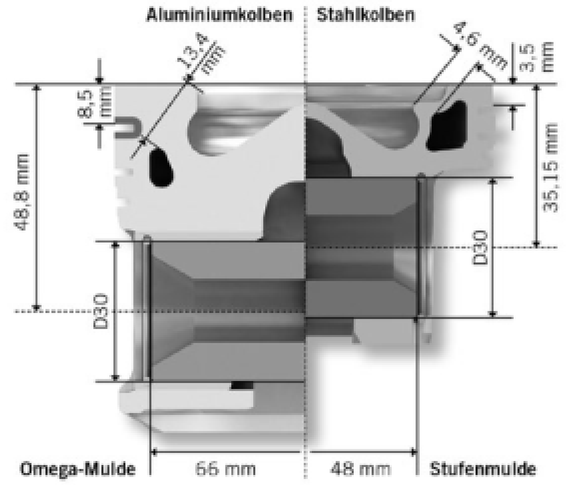
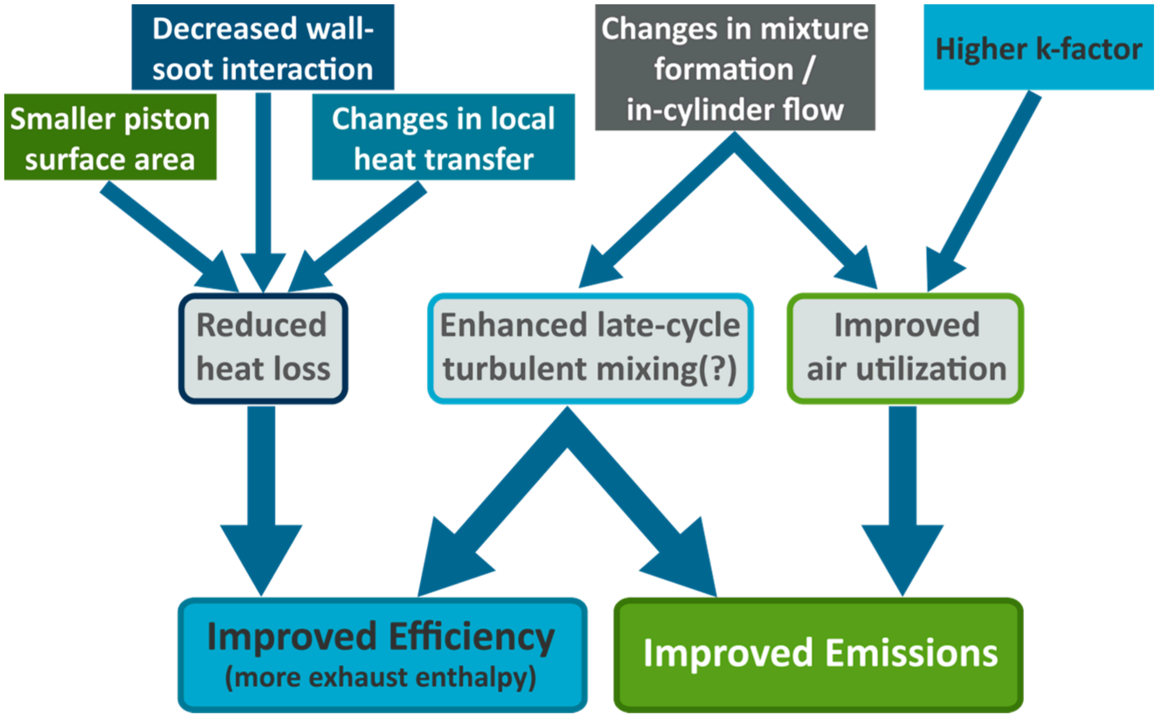


Bild 3: Alu-Kolben (Omega-Mulde) vs. Stahl-Kolben (Stufenmulde) (© Daimler)

From 1: Eder, T., Lückert, P., Kemmner, M., Sass, H. "OM654 – Start einer neuen Motorenfamilie bei Mercedes-Benz", *MTZ – Motortechische Zeitschrift* 77(3):62-69, 2016.
2: National Research Council. *Assessment of Fuel Economy Technologies for Light-Duty Vehicles.* Washington, DC: The National Academies Press, 2011. doi:10.17226/12924.

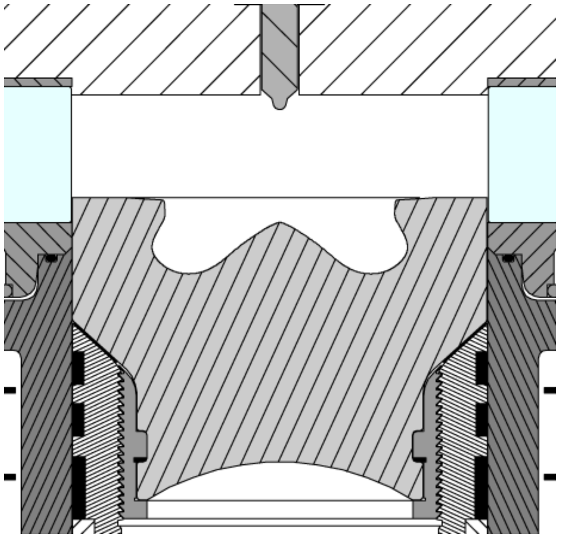
Understanding efficiency and emissions advantages with stepped-lip pistons

- The mechanisms responsible for these advantages are not well documented
- Limitations and drawbacks of stepped-lip pistons are not well understood
    - Spray targeting sensitivity
    - High speeds/loads
    - Others?
- Ultimate goal: detailed understanding of how piston geometry impacts efficiency and emissions



Experiments in the SNL light-duty single cylinder optical engine

- Initial performance testing with metal pistons: injection timing sweeps at fixed load
  - Conventional diesel c... : pilot-main injection ...gy
  - Low-tempera... com...ustion, single i...
- Off... ...s measure... ...ts w... ...uid HDA
- ...hermodynam...
  - F... ...d portion of ... ...heat loss
  - ...phasis on relativ...



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°

CRF

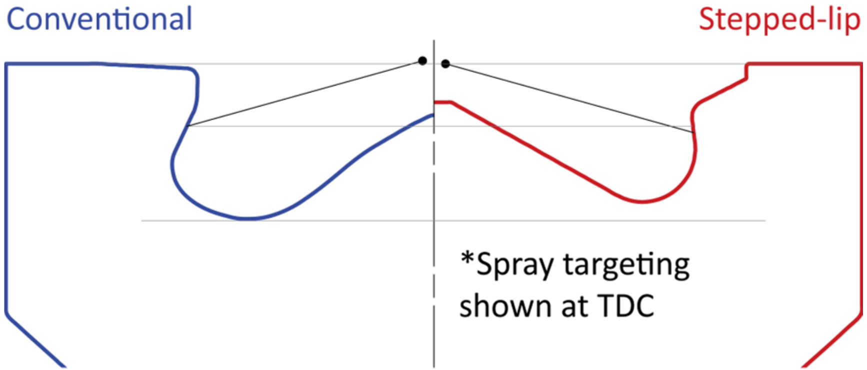
SNL piston bowl geometries

- Two piston geometries are compared:
  - Conventional, re-entrant bowl
  - Stepped-lip bowl
  - No valve cutouts

- The pistons have i … squish …ghts and bowl v…

… rea of stepped … wl is ~10 … s than for the … al bo…

- I … enetration i … d on … mendation … artners



Engine operation

- Skip-fired operation (1/5)
- Conventional diesel co n: pilot-main injection gy
- Block-s main w ustin duration t ntai
- Measure ure and

Engine speed	1500 rpm
$IMEP_g$	9.0 bar
Rail pressure	800 bar
m_{pilot}	1.5 mg/str
Pilot-main dwell	1200 µs
CA50	9.7-32 CAD ATDC
P_{intake}	150 kPa abs
T_{intake}	353 K
T_{TDC}	925 K (est.)
TDC density	21.8 kg/m^3
EGR	7% (10.3% accounting for residual fraction)
$[O_2]_{intake}$	19.73%
Fuel	DPRF58 (CN 50.7) 58 vol% Heptamethylnonane 42 vol% n-Hexadecane

Heat release analysis (with Woschni heat transfer model)

- Transient process analysis (ideal gas)

$$dQ_{HR} = \frac{1}{\gamma - 1}(VdP + \gamma PdV) + PdV + dQ_{wall}$$

$$dQ_{wall} = h_{Woschni} A_{cyl} \quad T_{wall})$$

$$h_{Woschni} = C\, B^{-0} \quad {}^{0.53} \quad {}^{0.8}$$

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  ... omposition
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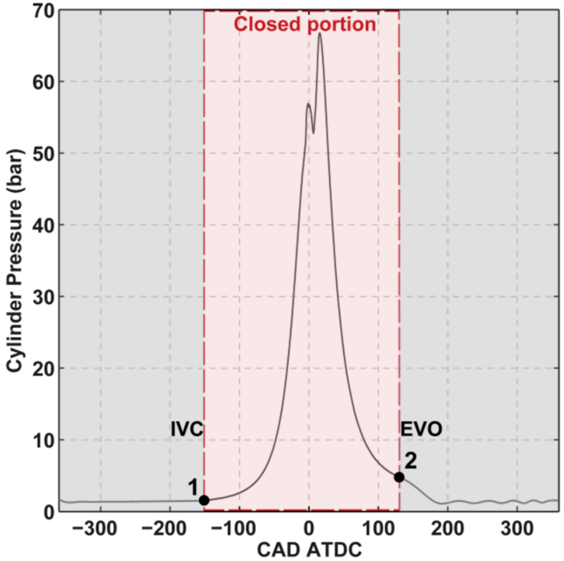


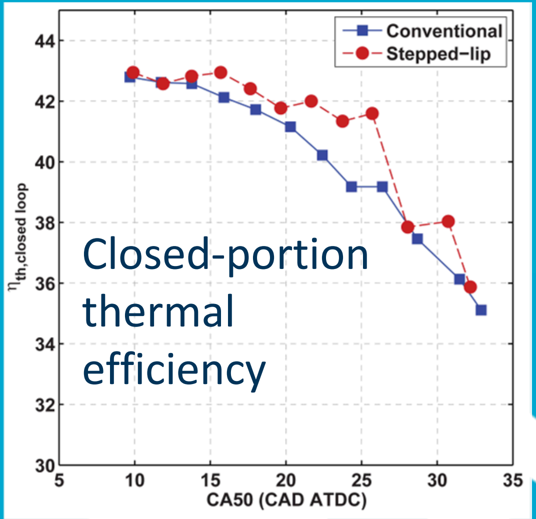
Integrated form of first law:

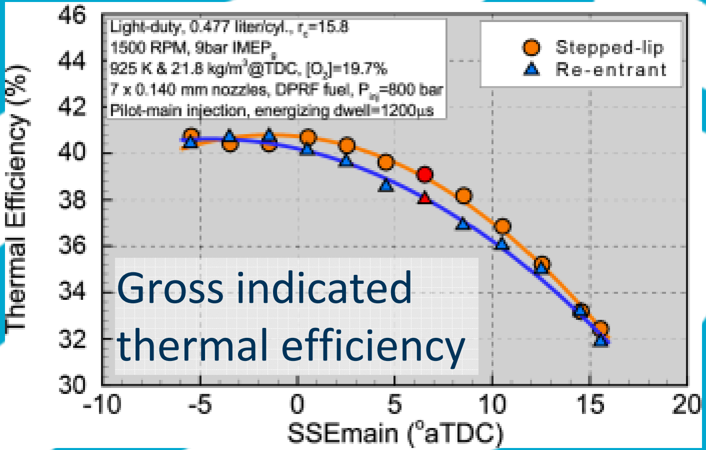
$$U_2 - U_1 = Q_{HR} - Q_{wall} - W + H_f$$

1: Heywood, J., “Internal Combustion Engine Fundamentals”, New York: McGraw-Hill, 1988.

Conventional combustion: thermal efficiency

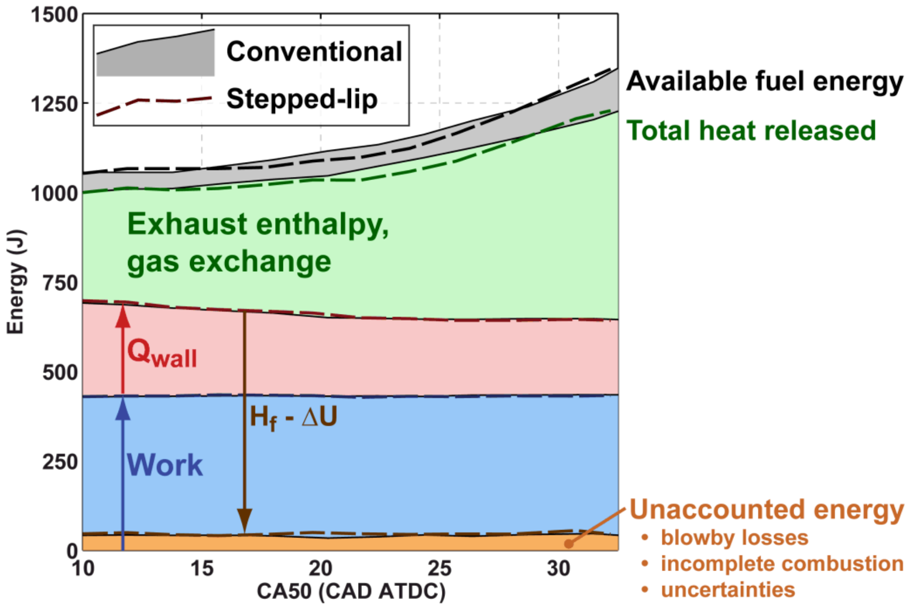
- Thermal efficiency can be higher with the stepped-lip piston
  - Benefit decreases at earliest and latest timings
  - A similar trend has been observed with gross indicated thermal efficiency
- Questions:
  - What is responsible for the efficiency benefit?
  - Why are the efficiency benefits only seen for a small range of injection timings?





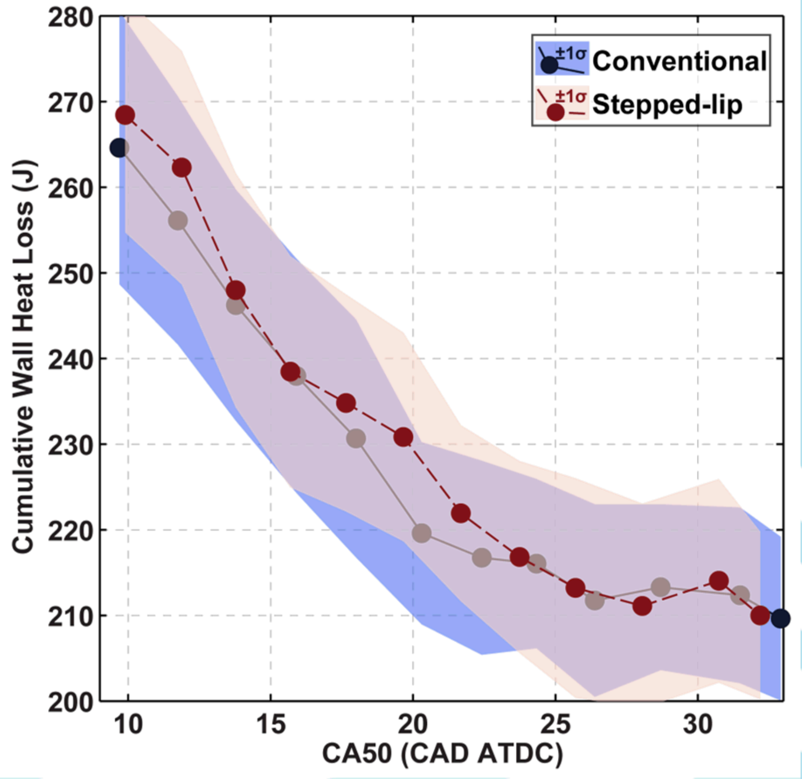
Conventional combustion: energy balance

- Losses / uncertainties result in 4-5% of the fuel energy being unaccounted for
  - Unaccounted energy magnitude is nearly independent of combustion phasing
  - The amount of unaccounted energy does not depend on piston geometry
- Wall heat loss decreases as combustion phasing is retarded
- No systematic difference in heat loss can be discerned



Conventional combustion: wall heat loss

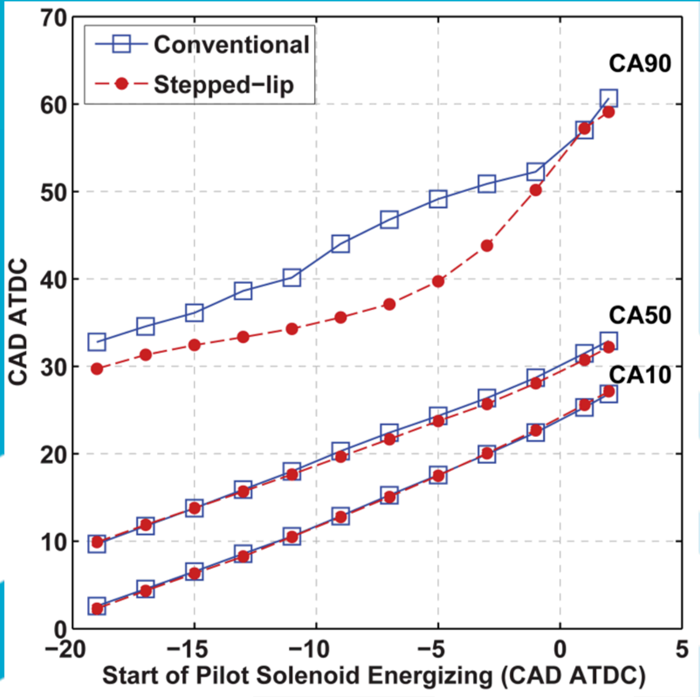
- Cycle-resolved analyses do not suggest lower wall heat loss with the stepped-lip piston bowl geometry
- Conclusion: we cannot resolve a difference in wall heat loss
  - With these piston bowl geometries
  - With this operating condition
  - With this experimental setup / simplified analysis
- What is responsible for the thermal efficiency improvement with the stepped-lip bowl?



Conventional combustion: late-cycle heat release

- Combustion phasing data
  - CA10-CA50 is unaffected by bowl geometry
  - CA50-CA90 duration can be much shorter with the stepped-lip bowl

- Could faster late-stage heat release lead to higher efficiency?

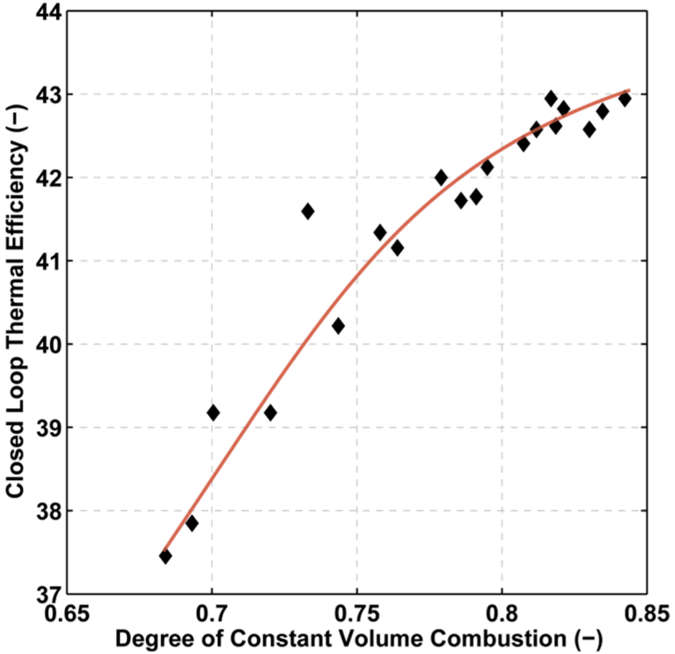


Conventional combustion: degree of constant volume combustion

- For equal compression ratio and heat losses, a higher degree of constant volume combustion should mean higher efficiency
- Degree of constant volume combustion[1]: to what extent does the cycle resemble an Otto cycle?

$$\eta_{CV} = \frac{1}{\eta_{Otto} Q_{HR}} \int 1 - \left(\frac{V_h + V_c}{V(\theta)}\right)^{1-\gamma} \frac{dQ_{HR}}{d\theta} d\theta$$

- The degree of constant volume combustion indeed correlates with thermal efficiency

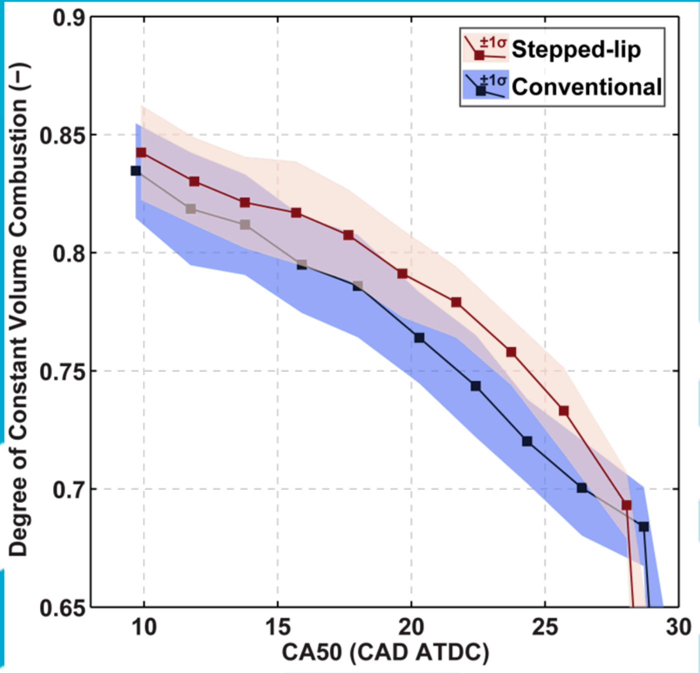


1: Shudo, T. and Nabetani, S., "Analysis of Degree of Constant Volume and Cooling Loss in a Hydrogen Fuelled SI Engine," SAE Technical Paper 2001-01-3561, 2001, doi:10.4271/2001-01-3561.

Conventional combustion: degree of constant volume combustion

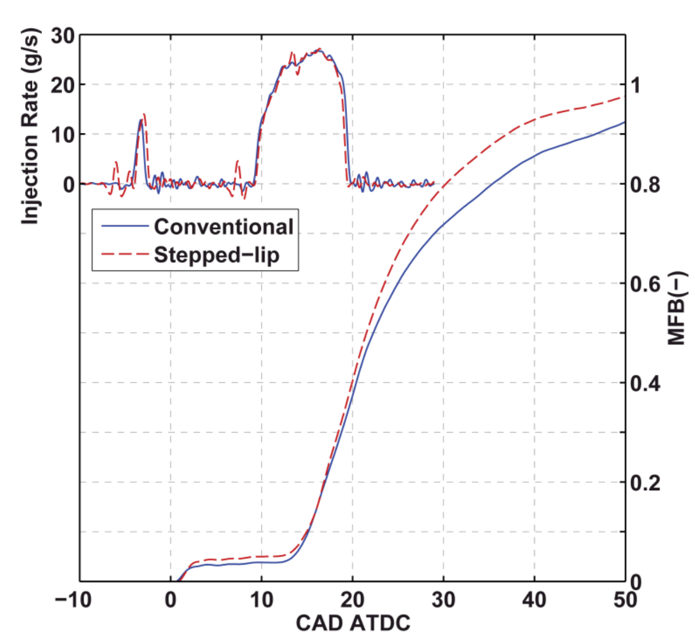
- On average, the degree of constant volume combustion is higher for the stepped-lip piston
- Largest differences in the degree of constant volume combustion coincide with the largest differences in efficiency

- Conclusion: for this configuration, efficiency improvements with the stepped-lip piston are most closely related to enhanced late-cycle heat release rates



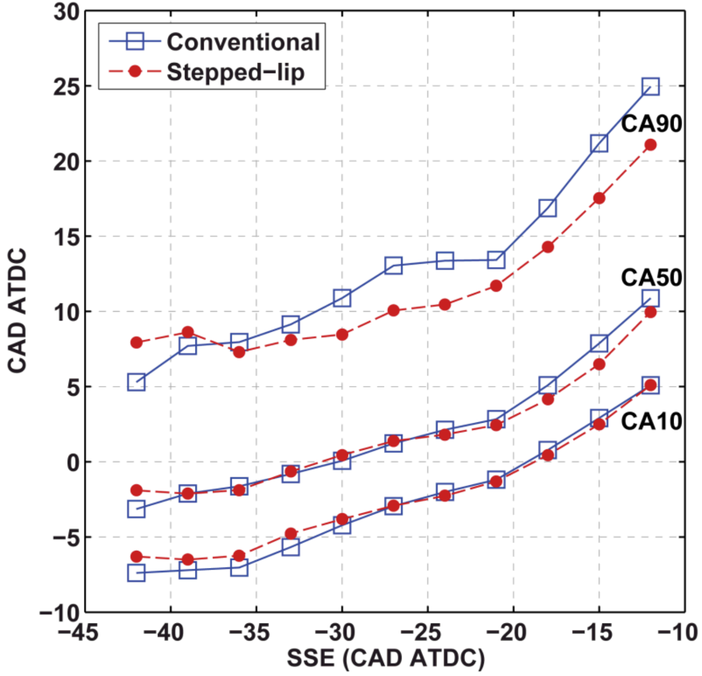
Conventional combustion: end of injection

- For more efficient operation, a shorter main injection duration is necessary to achieve a given load
- Can a shorter injection duration explain the change in CA90?
  - Doubtful
- The end of injection changes only slightly, whereas the heat release after CA50 changes dramatically



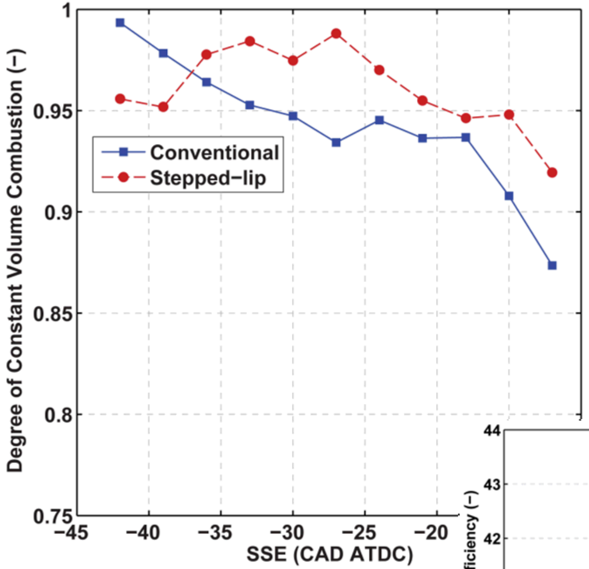
Low-temperature combustion: Combustion phasing

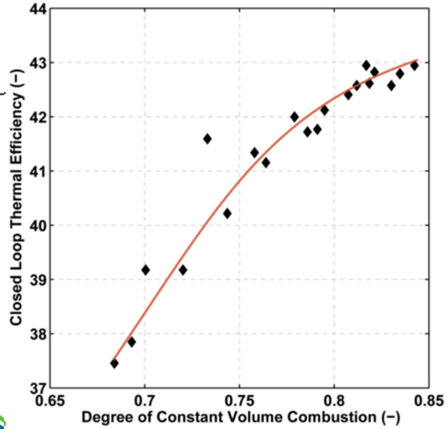
- Slight differences in CA10 appear for early injection timings
  - Leaner mixtures may form with the stepped-lip bowl
- CA50 is slightly … d with the stepped-li … te inje … tim … s
- … generally occu … r with the stepped-lip b …



Low-temperature combustion: Degree of constant volume combustion

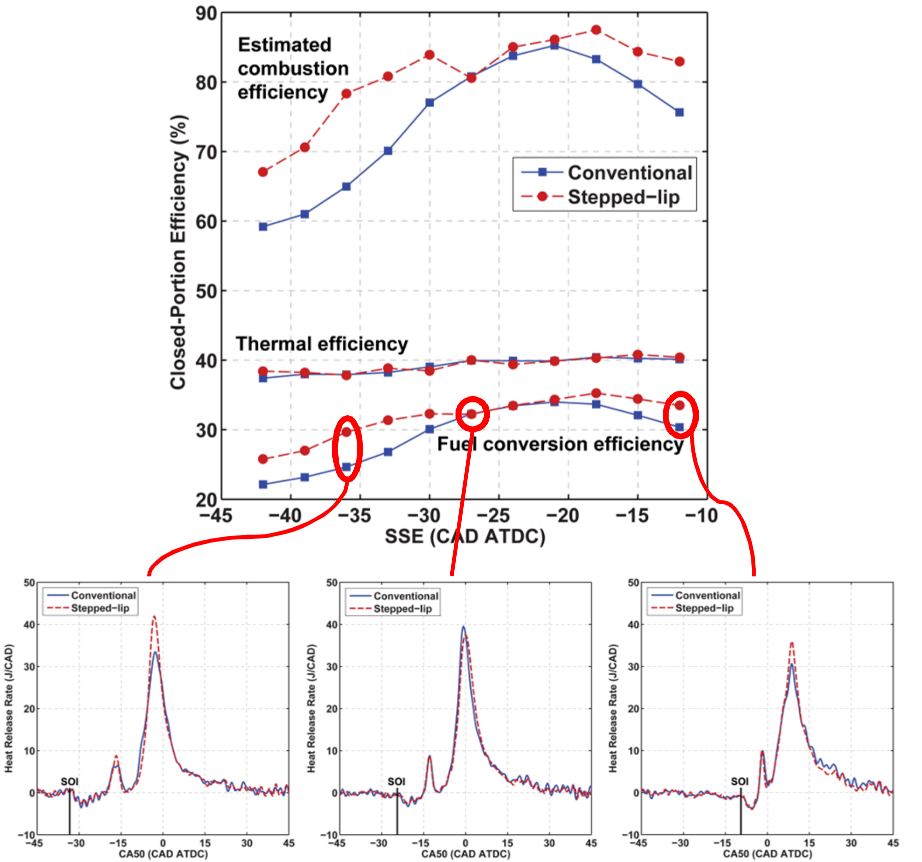
- For premixed, LTC conditions, the degree of constant volume combustion is generally high
- The degree of const olu combustion is t igher wit he stepped-li
- changes in th of constan volume comb a smal impa fficiency for ional combu e





Low-temperature combustion: Closed-portion efficiency

- Thermal efficiency is not significantly impacted by piston bowl geometry
- Combustion efficiency ...her for advanced and for re...d inj...ion timings with th... ...-lip bowl
- ...ustion effici...es ...spond with hig... ...k heat ...elease rates



Summary and conclusions

- SNL performance testing
    - Skip-fired operation in an optical engine
    - Conventional diesel combustion, pilot-main injection strategy
    - Offline fuel flow measurements
    - Piston geometry variation; injection timing sweep

- The stepped-lip piston leads to higher fuel conversion efficiencies for some injection timings
    - Differences in wall heat loss were not resolvable with a cylinder-pressure based analysis
    - Conventional diesel combustion: higher degree of constant volume combustion improves thermal efficiency
    - Low-temperature combustion: thermal efficiency does not improve, but combustion efficiency improves

Past, present, and planned work

- **Optical experiments: SNL**
  - Swirl-plane PIV measurements (previous studies)
  - Mixture formation processes (Kan's presentation: tomorrow at 08:10)
  - High-speed natural luminosity imaging: understanding flow patterns during combustion

- **Computational studies: UW**
  - First release of of new CFD coding platform (completed)
  - Cold flow simulations: impact of bowl geometry on in-cylinder flow (Federico's presentation: tomorrow at 08:45)
  - Impact of bowl geometry / fuel injection, on in-cylinder flow and mixing
    - Understanding the mechanisms for increased heat release rates and higher efficiencies
  - Drawbacks of stepped-lip pistons: speed / load / spray targeting sensitivities

Thank you for your attention

Questions?

Flow and turbulence dictate late-cycle fuel-air mixing processes

- Vertical-plane vortex structures transport fuel and oxidizer to a common location
- Fluid deformation and shear generate turbulence to enhance fuel-air mixing and enhance soot oxidation processes
- These flow structures are influenced by:
  - Swirl ratio
  - Injection timing / pressure
  - Bowl geometry
- CFD simulations (UW) will provide insight into these processes for the current study

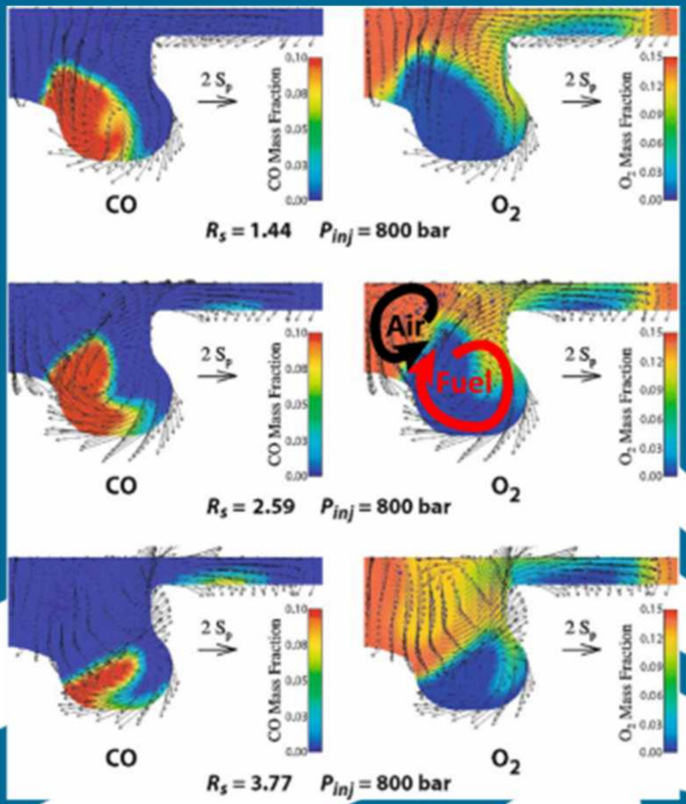


Fig. 4.34 The effect of swirl ratio on the distribution of partially burned fuel (CO) and oxidant at 17 CAD. In these simulations the premixed portion of combustion peaked at approximately 12 CAD, and these results correspond to the later, mixing-controlled burning. For these simulations, the flow was initialized with a solid-body-like mean velocity profile

From: Miles, P. C., "Turbulent Flow Structure in Direct-Injection, Swirl-Supported Diesel Engines", in Flow and Combustion in Reciprocating Engines, 2008, DOI: 10.1007/978-3-540-68901-0_4