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Experimental and Numerical Studies of Bowl Geometry Impacts on Thermal Efficiency in a Light-Duty Diesel Engine

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Light- and medium-duty diesel combustion system design

Swirl level

Injector nozzle parameters

Piston bowl geometry

Combustion system behavior
- Air utilization
- Emissions
- Efficiency

Focus of this work: conventional re-entrant vs. stepped-lip geometry

- **Impact on thermal efficiency**

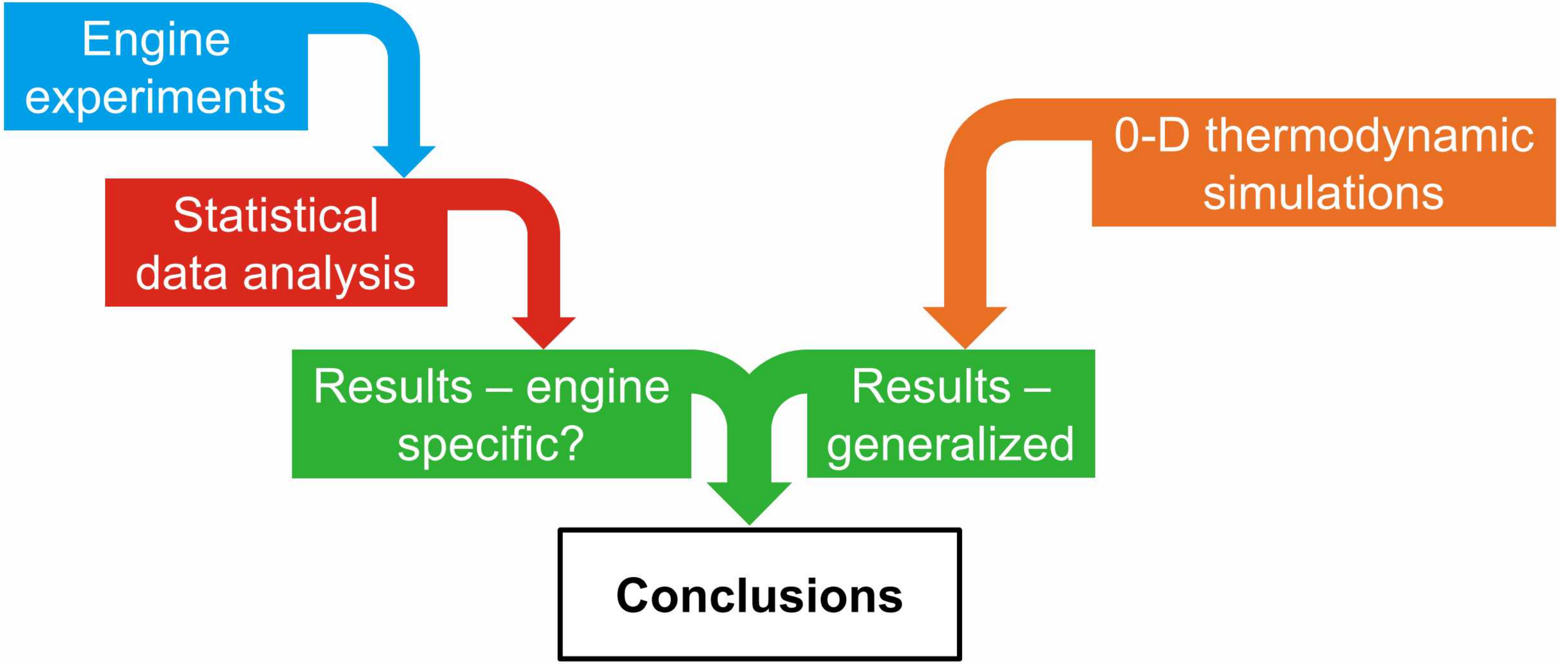
Efficiency advantages of stepped-lip pistons

	Change wall heat-loss			Change combustion duration
	Surface area/volume	Squish/swirl flow velocities	Jet-wall interactions	Mixing-controlled heat release
Stepped-lip advantage	Smaller	Possibly reduced	Unknown	Faster

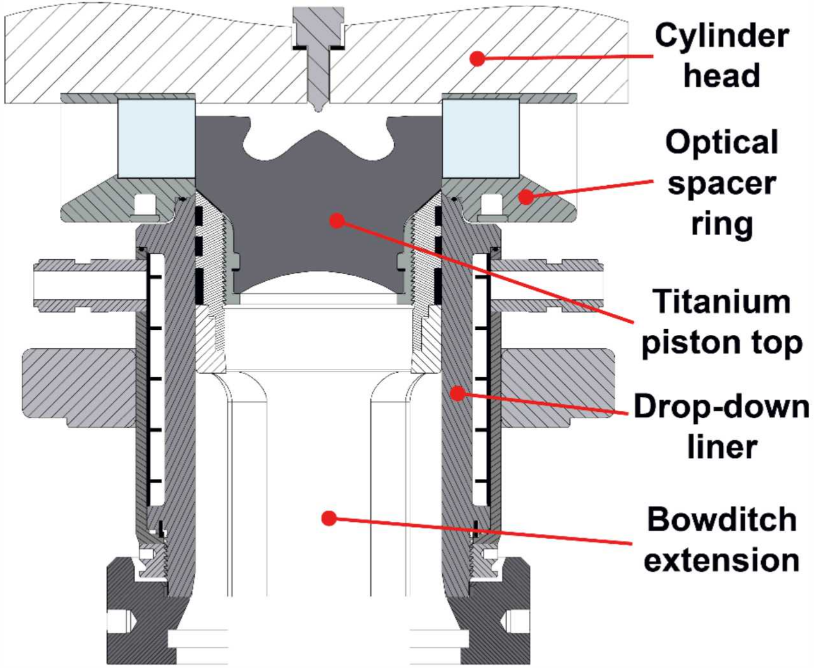
Questions addressed in this study:

- Is thermal efficiency higher with the stepped-lip piston?
- Which factors are responsible for the improvement?
- Can this be generalized for any geometry?

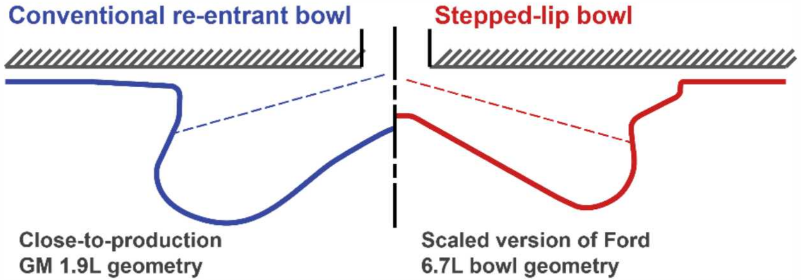
Overview of this work



Experimental setup

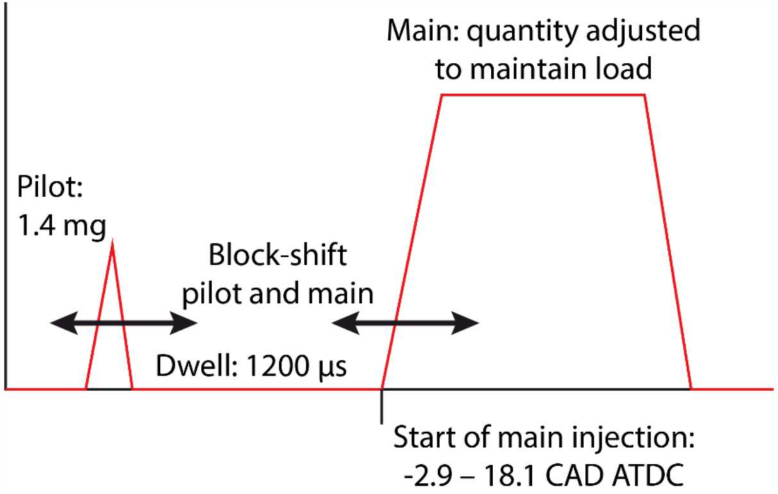


Bore	82.0 mm
Stroke	90.4 mm
Displacement volume	0.477 L
Geometric compression ratio	15.8:1



Engine operation (skip-fired)

Engine speed	1500 rpm
Swirl ratio	2.2
Injection pressure	800 bar
$IMEP_g$	9 bar
EGR rate (simulated)	7% + 3.3% residual fraction



Heat release analysis

- First-law, ideal-gas analysis

$$\frac{dQ_{hr}}{d\theta} = \frac{dQ_{wall}}{d\theta} + \frac{\gamma P \frac{dV}{d\theta} + V \frac{dP}{d\theta}}{\gamma - 1}$$

- Wall heat-loss computed with Woschni's correlation
- Analysis of closed portion of cycle (IVC – EVO)

Comparison metrics (cycle-resolved)

- Thermal efficiency:

$$\eta_{th} = \frac{\int_{V_{IVC}}^{V_{EVO}} P dV}{Q_{hr,total}}$$

- Normalized wall heat-loss:

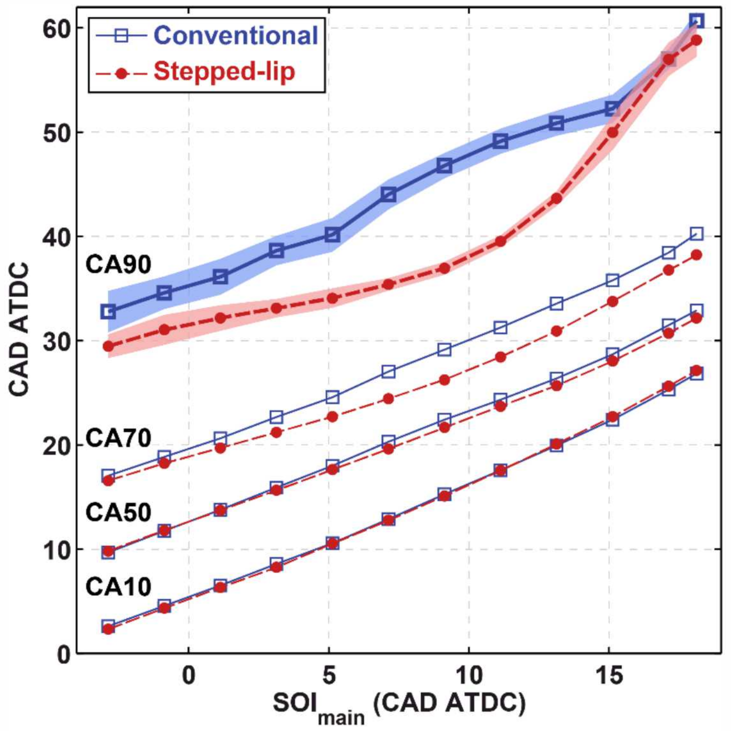
$$Q_w^* = \frac{\int_{IVC}^{EVO} \frac{dQ_w}{d\theta} d\theta}{Q_{hr,total}}$$

- Degree of constant volume combustion:

$$dCVC = \frac{1}{\eta_{otto} Q_{hr,total}} \int \left(1 - \left(\frac{V_d + V_c}{V(\theta)}\right)^{1-\gamma} \frac{dQ_{hr}}{d\theta}\right)$$

Bowl geometry effect on injection timing and combustion phasing

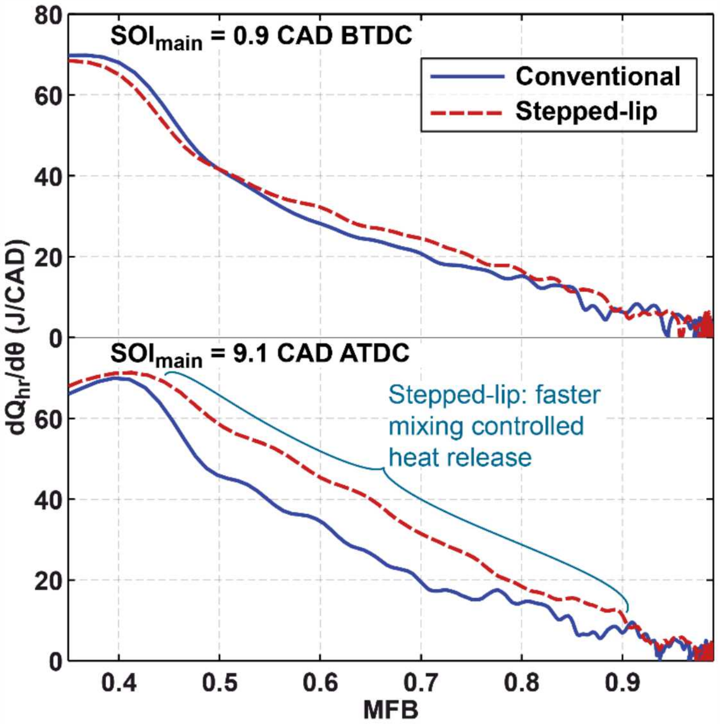
- Combustion phasing retards with injection timing
- Bowl geometry has very little impact before CA50
- After CA50, heat release is often faster with the stepped-lip piston
  - This effect depends on injection timing



Bowl geometry effect on mixing-controlled heat release rates

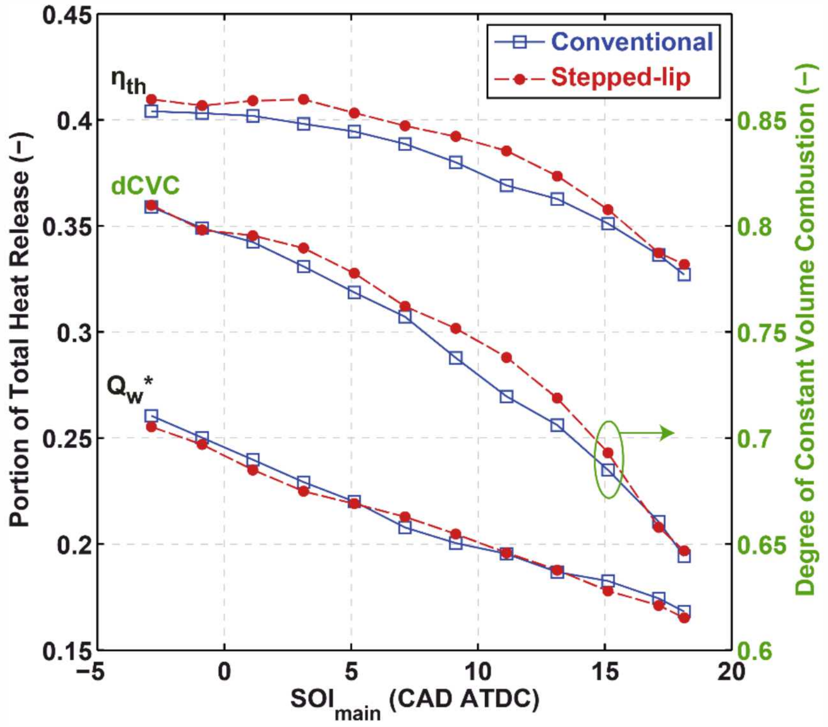
- Top plot: mixing-controlled heat-release rates are modestly increased with the stepped-lip piston after CA50

- Bottom plot: significant increase in heat-release rates with stepped-lip piston
  - After CA50
  - After heat-release rate reaches its maximum



Bowl geometry effect on thermal efficiency, wall heat loss, and dCVC

- Thermal efficiency improves with the stepped-lip piston for intermediate injection timings
- Normalized wall heat loss may increase or decrease, depending on injection timing
- The degree of constant volume combustion is higher with the stepped-lip piston for intermediate injection timings



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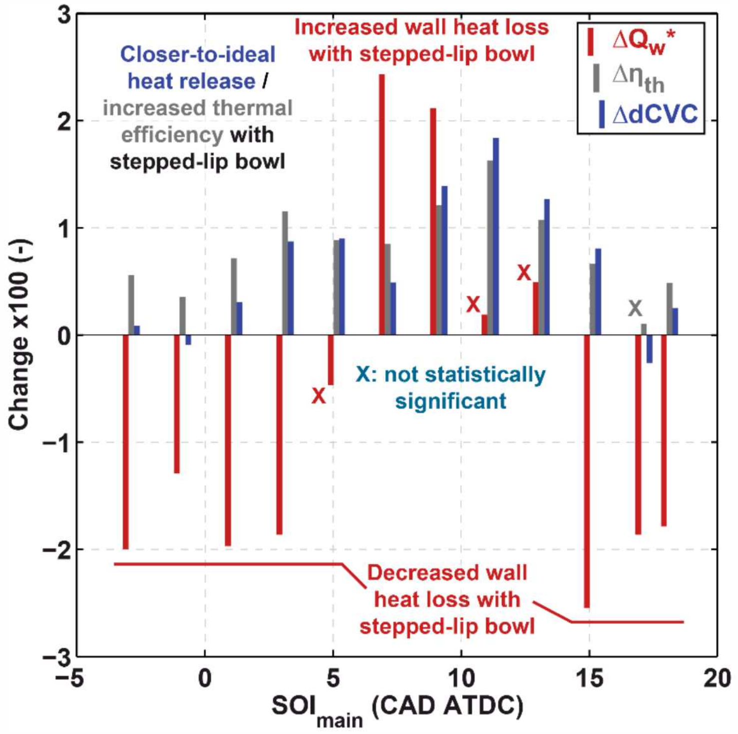
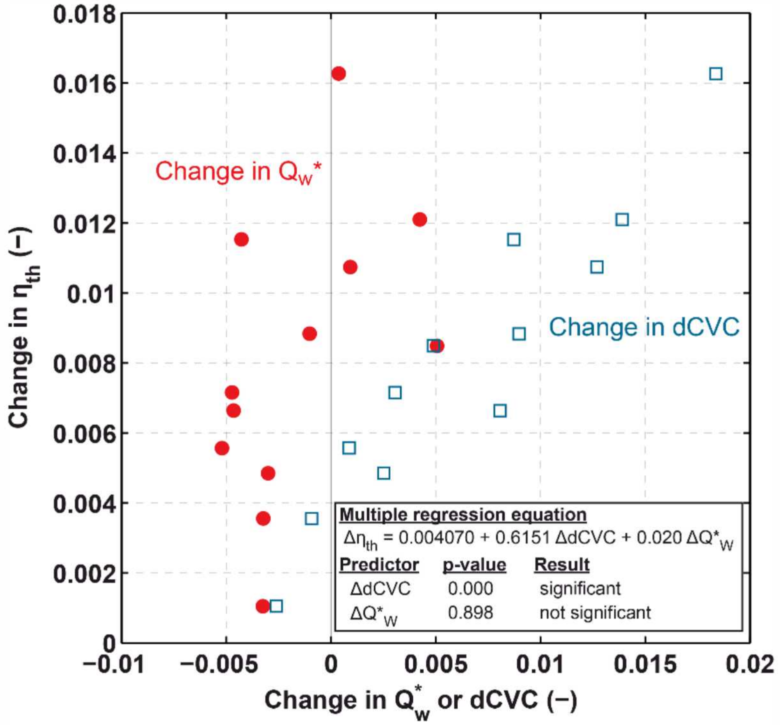
Changes in thermal efficiency – wall heat loss or faster combustion?

- Thermal efficiency improves by as much as 1.6 percentage points at intermediate injection timings with the stepped-lip piston
- Efficiency improvements do not appear to correlate with changes in wall heat-loss
- The change in the degree of constant volume combustion correlates well with the improvement in efficiency



Regression analysis

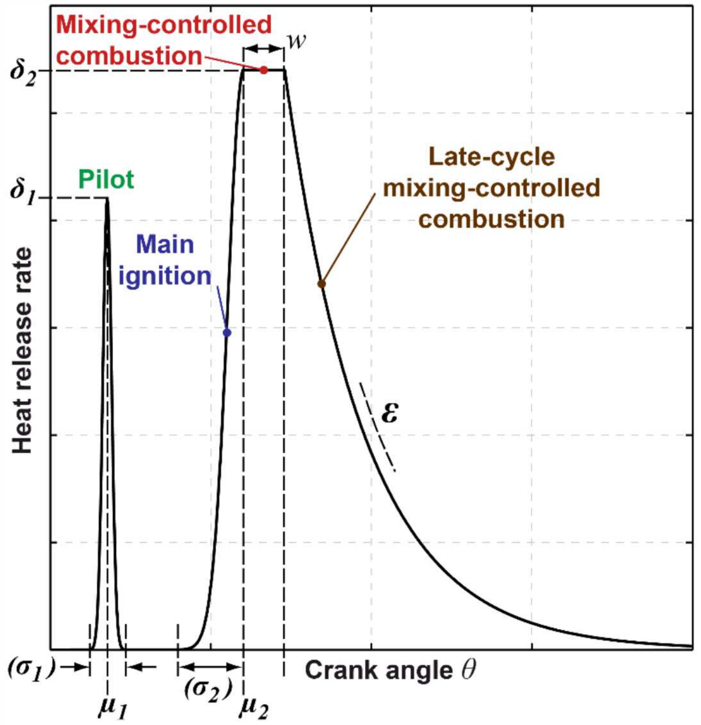
- Wall heat-loss changes can account for no more than 25% of the variability in efficiency change
- Changes in the degree of constant volume combustion account for nearly 90% of the observed variability in efficiency change
- Change in wall heat loss is not a statistically meaningful predictor of change in thermal efficiency



Simplified analyses via 0-D thermodynamic simulations

- Use first law and ideal gas law to compute cylinder pressure for pre-defined heat-release profiles
  - Heat-release profiles defined by Gaussian-like parameters
  - Parameter w varied to maintain load

- Included effects:
  - Wall heat loss
  - Temperature dependence of γ



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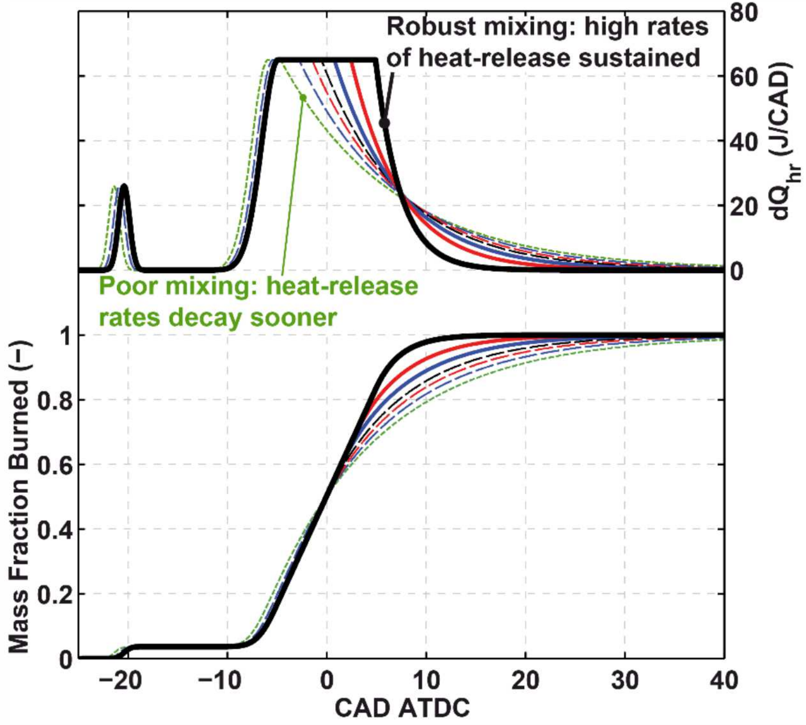
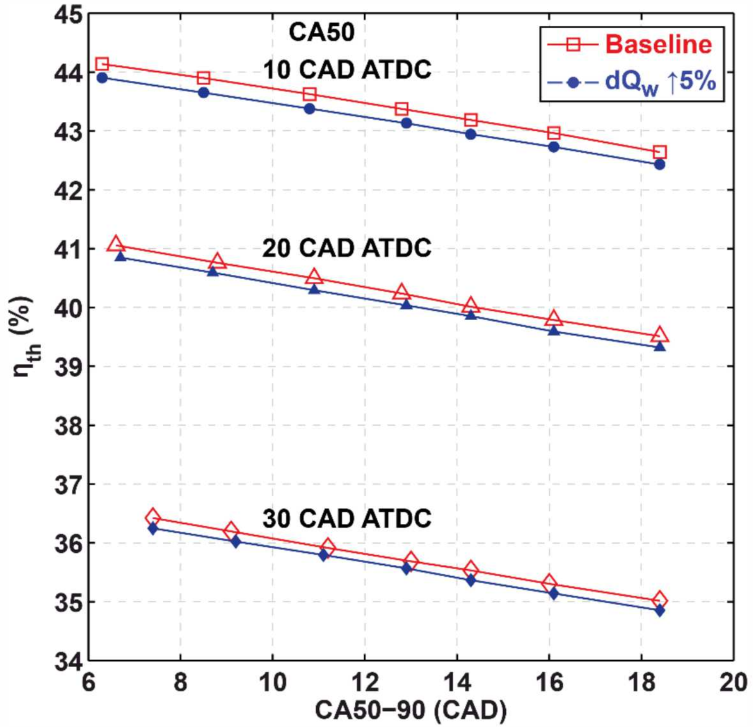
0-D simulation methodology

- For a given CA50 value, vary the simulated mixing-controlled combustion behavior and convection coefficient
- Iteratively adjust duration of heat release to achieve target IMEP for each case
- Compute cylinder pressure traces and efficiencies



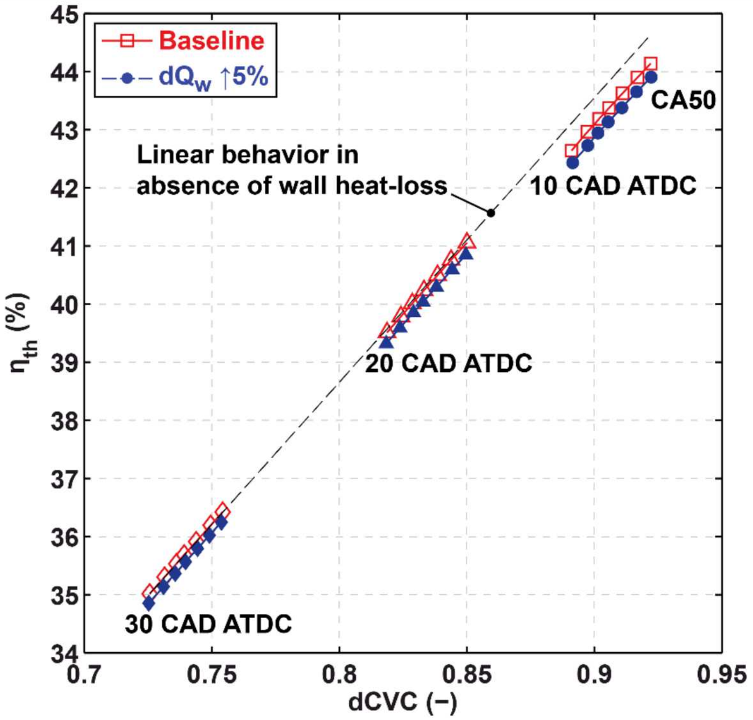
Results of 0-D thermodynamic simulations

- Simple models capture the effect of combustion phasing on efficiency
- Increasing wall heat loss decreases efficiency
- For a given CA50, efficiency increases as CA50-90 decreases



Relationship between η_{th} and dCVC

- η_{th} varies nearly linearly with dCVC
- Wall heat-loss makes the trend non-linear, and becomes more important as CA50 is advanced
- dCVC captures both combustion phasing and duration effects
- Decreasing wall heat-loss is less effective than improving dCVC to increase efficiency



Summary of findings

- Engine experiments
  - Wall heat-loss may increase or decrease with this piston geometry change
  - Faster mixing-controlled heat-release correlates with thermal efficiency gain, but changes in wall heat-loss do not
  - Use of the stepped-lip piston improves efficiency most effectively for main injections starting between 3 and 13 CAD ATDC

- 0-D simulations
  - Changing CA50-90 changes the degree of constant volume combustion, and is more effective than decreasing wall heat-loss to improve thermal efficiency

Conclusions and next steps

- Because piston bowl geometry affects mixing controlled heat-release rates, it can directly impact thermal efficiency

- We need to understand the mechanisms responsible for changes in turbulent mixing rates as piston geometry changes
  - Experimental characterization of flow during mixing-controlled phase of combustion (Zha et al., 2018-01-0230)
  - Analysis of CFD simulations to reveal the physics that create beneficial flow structures in the stepped-lip combustion chamber
    - Planned publication at SAE PFL Meeting, Heidelberg, Sept. 2018

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Thank you

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